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NOx EMISSION STUDY:
An Investigation of Water-Based Emission Control Technologies

Prepared for
Transportation Development Centre
of
Transport Canada

by

FLEETWAY Inc.

800 - 141 Laurier Avenue West
Ottawa, Ontario
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October 2005

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NOTICES

This report reflects the views of the authors and not necessarily those of the Transportation Development Centre of Transport Canada.

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

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16. Abstract

This report investigates the reduction of NOx emissions from marine diesel exhaust using water-based technologies. The review was based on a detailed literature survey and analysis of available data from testbed and shipboard trials, specifically on the following water based reduction systems:

i) Intake air humidification / water injection
ii) Water injection directly into the combustion chamber via a separate nozzle
iii) Water injection directly into the combustion chamber via the same nozzle as fuel (stratified fuel-water-fuel injection)
iv) Water injection by fuel-water emulsion

The report examines these water injection technologies and explains the underlying science and the effects of variation in process parameters. The primary mechanisms for NOx formation during combustion are (i) Thermal NO, (ii) Prompt NO, (iii) N_2O Pathway, and (iv) Fuel Nitrogen Pathway. Process parameters that influence NOx formation – i.e., quantity of reactants, pressure, temperature, etc. – may effect a change in the quantity of NOx formed.

Theoretical and experimental evidence indicates that NOx reduction by water injection into the inlet manifold / air intake ranges from 10 to 80 percent, direct/stratified water injection from 20 to 50 percent, and fuel-water emulsions 10 to 50 percent. However, NOx emission reduction can negatively affect (increase) other exhaust emissions such as particulate matter, carbon monoxide, carbon dioxide, total hydrocarbons, and smoke. In addition, water injection can also influence fuel consumption and engine maintenance.

New engines equipped with stratified injection can direct a more precise stream of water to the combustion zone, thus reducing thermal NO formation. For retrofit applications, trial data show that simple intake air water injection systems can effectively reduce NOx emissions up to about 34 percent. Depending on engine type and age, this may be sufficient to make older engines IMO compliant (MARPOL Annex VI criteria).

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16. Résumé

Ce rapport traite du recours à des technologies fondées sur l'injection d'eau pour réduire les émissions de NO_x générées par les moteurs diesel marins. L'étude a commencé par une recherche documentaire fouillée et par l'analyse des données recueillies au cours d'essais au banc et d'essais en vraie grandeur. Voici les principales technologies d'injection d'eau sur lesquelles a porté la recherche :

i) humidification de l'air d'admission / injection d'eau dans l'air d'admission
ii) injection directe d'eau dans la chambre de combustion, au moyen d'un injecteur distinct
iii) injection d'eau directement dans la chambre de combustion, au moyen de l'injecteur à mazout (injection stratifiée d'eau et de mazout)
iv) injection d'une émulsion eau-mazout

Le rapport examine ces diverses technologies d'injection d'eau, explique les principes qui les sous-tendent et examine les effets de la variation de leurs paramètres de fonctionnement. Les principaux mécanismes qui entraînent la formation de NO_x au cours de la combustion sont (i) les NO d'origine thermique, (ii) les NO spontanés, (iii) les précurseurs de N_2O et (iv) les précurseurs d'azote du combustible. Par ailleurs, les paramètres de fonctionnement qui influent sur la formation de NO_x – c.-à-d. la quantité de réactifs, la pression, la température, etc. – peuvent avoir un effet sur la quantité des NO_x formés au cours de la combustion.

Selon les données théoriques et expérimentales examinées, l'injection d'eau dans la tubulure/l'air d'admission entraîne une réduction de 10 à 80 p. 100 des NO_x, l'injection directe/stratifiée d'eau, une réduction de 20 à 50 p. 100, et les émulsions eau-mazout, une diminution de 10 à 50 p. 100. Toutefois, dans tous les cas, la réduction des émissions de NO_x peut avoir un effet négatif (multiplicateur) sur les autres émissions, comme les particules, le monoxyde de carbone, le dioxyde carbone, les hydrocarbures totaux et la fumée. De plus, l'injection d'eau peut aussi influer sur la consommation de carburant et sur l'entretien du moteur.

Les nouveaux moteurs équipés d'un système d'injection stratifiée peuvent diriger avec plus de précision un jet d'eau dans la zone de combustion, ce qui prévient la formation de NO d'origine thermique. Pour les installations en rattrapage, les données d'essai indiquent que de simples systèmes d'injection d'eau dans l'air d'admission peuvent effectivement réduire jusqu'à 34 p. 100 les émissions de NO_x. Selon le type et l'âge du moteur, cela peut suffire à rendre des moteurs anciens conformes aux règles de l'OMI (aux critères de l'annexe VI de la convention MARPOL).

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EXECUTIVE SUMMARY

Canada is a member of the International Maritime Organization (IMO), a UN specialized agency that develops international marine safety regulations. The regulations incorporated under Annex VI of IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) entered into force in May 2005. These regulations define limits for sulphur oxides (SOx) and nitrogen oxides (NOx) emissions from ship exhausts. Canada currently proposes to ratify MARPOL Annex VI by 2006/07.

As part of its commitment to protect the environment and to achieve a more sustainable transportation system, the Transportation Development Centre of Transport Canada commissioned this study to investigate Water Injection System (WIS) technologies to reduce NOx exhaust emissions from marine diesel engines. The Canadian ratification of MARPOL Annex VI will require changes to Canadian regulations. This study provides a partial technical basis for these regulatory changes on the premise that regulations must be practically achievable.

The main objectives of the NOx Emission Study were to examine the underlying mechanism behind NOx reduction via water injection, and the effect(s) of WIS operation on other exhaust emissions and engine operation. The study focussed on three primary WIS methods: (i) intake air humidification / water injection, (ii) direct in-cylinder water (separate or stratified nozzle), and (iii) fuel-water emulsions.

A detailed survey of prevailing literature and assay of existing NOx emission datasets were completed as the foundation of this study. This study provides a rational framework for the reason water injection achieves NOx reduction and the effects on exhaust emissions and engine operation.

Theoretical and experimental evidence indicates that NOx reductions due to various water injection modes range from 10 to 80 percent for intake air humidification / water injection, 20 to 50 percent for direct injection and 10 to 50 percent for fuel-water emulsions. The effects of water on other emissions, such as particulate matter, carbon monoxide, total hydrocarbons and smoke, also vary for each method; NOx reduction is often accompanied by increases in other emission products. WIS design thus becomes an optimization problem of maximizing NOx reduction while minimizing the increase of other emissions.

These emission considerations must also be balanced with system cost and the effect on fuel consumption and maintenance. Depending on the type of installation (i.e., for retrofit of existing vessels), a simple intake air water injection system, which can reduce NOx emissions up to about 34 percent, may be more cost effective. For new built vessels, engines equipped with stratified injection (fuel-water-fuel through the same injector) can achieve a more precise water placement to the combustion zone, thus reducing thermal NOx formation. The major drawback of stratified direct water injection in comparison with individual water and fuel injectors is that the system design is complex and costly, involving a complicated nozzle and considerable modification to the existing system. Direct water injection (DWI) using a separate nozzle is a good option for overall engine operability that allows simple control over the amount of water injected and has minimal effect on cold start and lubricating oil water contamination. Test data show that a simple DWI system can yield a substantial reduction in NOx emissions (on the order of 30 percent).

SOMMAIRE

Le Canada est un des pays membres de l'Organisation maritime internationale (OMI), un organisme spécialisé de l'ONU qui élabore des règlements internationaux sur la sécurité maritime. Les règlements qui forment l'annexe VI de la Convention internationale pour la prévention de la pollution par les navires (MARPOL) de l'OMI sont entrés en vigueur en mai 2005. Ces règlements établissent des limites relativement aux émissions d'oxydes de soufre (SO_x) et d'oxydes d'azote (NO_x) produites par les navires. Le Canada se propose de ratifier d'ici 2007 l'annexe VI de la Convention MARPOL.

Pour appuyer son engagement envers la protection de l'environnement et un système de transport plus durable, le Centre de développement des transports de Transports Canada a commandé la présente étude, qui explore la capacité des technologies d'injection d'eau (WIS, pour *Water Injection System*) à réduire les émissions de NO_x produites par les moteurs diesel marins. La ratification par le Canada de l'annexe VI de la Convention MARPOL nécessitera des modifications aux règlements canadiens. La présente étude pose une partie des bases techniques sur lesquelles fonder ces modifications, selon le principe que tout règlement doit être concrètement applicable.

L'étude sur les émissions de NO_x visait avant tout à mieux comprendre comment l'injection d'eau dans le moteur permet de réduire les NO_x, et à cerner les effets de l'injection d'eau sur les autres émissions et sur le fonctionnement du moteur. L'étude a porté sur trois méthodes d'injection d'eau : (i) humidification de l'air d'admission / injection d'eau dans l'air d'admission, (ii) injection directe d'eau dans le cylindre (injecteur distinct ou injection stratifiée), (iii) émulsions eau-mazout.

L'étude a commencé par une recherche documentaire fouillée et par l'examen d'ensembles de données sur les émissions de NO_x. Le rapport explique comment l'injection d'eau entraîne une réduction des NO_x et expose les effets de cette technique sur l'ensemble des émissions de gaz polluants et sur le fonctionnement du moteur.

Selon les données théoriques et expérimentales examinées, l'injection d'eau dans la tubulure/l'air d'admission entraîne une réduction de 10 à 80 p. 100 des NO_x, l'injection directe d'eau, une réduction de 20 à 50 p. 100, et les émulsions eau-mazout, une diminution de 10 à 50 p. 100. Les effets de l'injection d'eau sur les autres émissions, comme les particules, le monoxyde de carbone, les hydrocarbures totaux et la fumée, varient eux aussi beaucoup selon la méthode; ainsi, la réduction de NO_x s'accompagne souvent d'une augmentation d'autres types d'émissions. Le problème, avec les systèmes d'injection d'eau, se pose donc davantage en termes d'optimisation que de conception, le but étant de maximiser la réduction des NO_x tout en limitant l'augmentation des autres émissions.

Au-delà des considérations relatives aux émissions, il y a aussi un équilibre à trouver en ce qui a trait au coût du système et à ses effets sur la consommation de carburant et l'entretien du moteur. Pour ce qui est du coût, un simple système d'injection d'eau dans l'air d'admission, qui peut réduire jusqu'à environ 34 p. 100 les émissions de NO_x, peut représenter la solution la plus rentable dans le cas d'une installation en rattrapage. Pour les navires neufs, il convient de privilégier les systèmes d'injection stratifiée (dans lesquels le mazout et l'eau passent tour à tour par le même injecteur), qui orientent de façon plus précise le jet d'eau dans la zone de combustion, réduisant ainsi la formation de NO_x d'origine thermique. Mais l'injection stratifiée est complexe et coûteuse par rapport à l'injection distincte d'eau et de mazout. En effet, elle fait appel à un injecteur compliqué et elle nécessite des modifications majeures au système existant. L'injection directe par des injecteurs distincts est un choix intéressant du point de vue du fonctionnement global du moteur, car elle permet de commander facilement la quantité d'eau injectée, sans avoir d'effet majeur sur le démarrage à froid et sur la contamination de l'huile de lubrification par l'eau. Les données d'essai révèlent qu'un simple système d'injection directe d'eau peut engendrer une réduction substantielle des émissions de NO_x (de l'ordre de 30 p. 100).

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DEFINITIONS

Brake Specific Fuel Consumption

The ratio of fuel consumed to power produced. This ratio is a direct indicator of how efficiently the engine converts fuel into power.

Cetane Number

The cetane number measures the ignition quality of a diesel fuel (similar to gasoline's octane number). The rating compares a fuel's performance in a standard engine with that of a mixture of cetane and alpha-methyl-naphthalene. The cetane number is the percentage by volume of cetane in the mixture that has the same performance as the fuel.

Effectiveness (NOx reduction)

A measure of comparison between different water injection systems that normailzes by W/F ratio. Effectiveness is defined as:

$$\text{Effectiveness} = (1 - NOx_{WIS} / NOx_{BASE}) / ({MASS}_{water} / {MASS}_{fuel})$$

where, NOx_{WIS} = NOx emission rate (i.e. g/kWh) with WIS
NOx_{BASE} = NOx emission rate without WIS active (same load)
${MASS}_{water}$ = Mass flow of water
${MASS}_{fuel}$ = Mass flow of fuel

Engine Knocking

Knocking is a dramatic and sudden increase in cylinder pressure and temperature that is sometimes audible outside the engine. Knocking induces shock waves in the combustion chamber, which can result in high instantaneous loads on various engine components. Knocking is caused when combustion occurs instantaneously, as opposed to gradually, as fuel is injected. Causes may include poor fuel quality, poor fuel atomization, low compression temperature and low combustion temperature.

Emissions Test Cycle

Engine emission characteristics change depending on engine loading. The test cycle is a method of normalization used to present more meaningful emissions results. The engine's expected duty cycle is divided into a number of operating 'modes' where engine speed and power are defined. Weighting factors are assigned to each mode (representative of the fraction of time the engine would be expected to operate in that mode). Testing is completed at each mode and emission results reported as cycle weighted = Σ (mode n result) x (mode n weighting factor). Steady-state test cycles for marine (non-road) engines are defined in ISO 8178-4 [50].

Intercooler

The intercooler (charge air cooler, aftercooler) is typically used in conjunction with a turbocharger and/or supercharger to further increase engine power by cooling the pressurized air output from the compressor. Cooler air has higher density and thus increases the mass of oxygen in the cylinder (more fuel can be combusted).

Supercharger

Similar to turbocharger (see below) except turbine is mechanically driven (i.e. connected via belt to engine).

Turbocharger

A forced induction system consisting of a turbine and compressor combination used to increase engine power output by compressing the intake air. This increases the mass of oxygen in the cylinder (more fuel can be combusted). Exhaust gas drives the turbine, which is connected by a short shaft to the compressor located between the air filter and the engine's intake air manifold.

ABBREVIATIONS

ORGANIZATIONAL

EC	Environment Canada
EPA	Environmental Protection Agency (U.S.)
ERMD	Emissions Research and Measurement Division (EC)
EU	European Union
IMO	International Maritime Organization
MARPOL	International Convention for the Prevention of Pollution from Ships (IMO)
TC	Transport Canada
TDC	Transportation Development Centre (TC)

TECHNICAL

ASI	After the Start of Injection
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CWI	Continuous Water Injection
DWI	Direct Water Injection
EGR	Exhaust Gas Re-circulation
GHG	Greenhouse Gas
HAM	Humid Air Motor
HFO	Heavy Fuel Oil
IFO	Intermediate Fuel Oil
NOx	Nitrogen Oxides
MCR	Maximum Continuous Rating (engine)
MDO	Marine Diesel Oil
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SFC	Specific Fuel Consumption
SOI	Start of Injection
TCH	Total Hydro-Carbons
WIS	Water Injection System
W/F	Water-to-Fuel (weight based)

UNITS

bhp	brake horsepower (at engine)
°C	degree Celsius (temperature)
CAD	Crank Angle Degrees
cSt	centistoke (kinematic viscosity) = 1×10^{-6} m^2/second
g	gram
hp	horsepower
K	degree Kelvin (temperature)
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
L	litre
m	metre
psi	pounds per square inch (absolute pressure)
psig	pounds per square inch (gauge pressure)
µm	micrometre (one millionth of a metre $mx10^{-6}$)

1. INTRODUCTION

1.1 Background

There is international effort focussed on the reduction of gaseous emissions that contribute to global warming and atmospheric pollution. Ships are responsible for a portion of this pollution contributing to environmental degradation. Exhaust from marine diesel engines includes air pollution in the form of nitrogen oxides (NOx), carbon oxides (CO, CO_2), unburned hydrocarbons (THC) and particulate matter (PM). These have been proven to have a negative impact on health and the environment. Increasingly, these marine sources are being targeted for reduction. The focus of many government and industry-based marine transportation environmental initiatives is the diesel engine, as significant quantities of NOx and PM are associated with diesel combustion.

In Canada, the total nation-wide NOx emissions attributed to marine transportation as reported by Environment Canada [1] is approximately 3.7%. By comparison, marine transportation accounts for approximately 14% of total global NOx emissions. As may be expected, these numbers vary greatly between geographic locations, as marine activity is concentrated in port areas.

The International Maritime Organization (IMO) is a specialized agency of the UN responsible for measures to improve the safety of international shipping and to prevent marine pollution from ships. One of IMO's primary conventions is the International Convention for the Prevention of Pollution from Ships (MARPOL). Annex VI of MARPOL, Prevention of Air Pollution from Ships, entered into force on 19 May 2005. Annex VI sets limits on sulphur oxide (SOx) and nitrogen oxide (NOx) emissions from ship exhausts, and prohibits the deliberate emission of ozone depleting substances. This will have immediate effect on new engines installed or existing engines undergoing major conversion on or after this date. Canada currently proposes to ratify MARPOL Annex VI by 2006/07.

Modifications to engines can effectively reduce NOx emissions. Many manufacturers are altering engine designs to meet worldwide regulatory requirements for low NOx emissions. However, when simple engine modifications cannot provide the necessary reductions, more extensive NOx emissions reduction technologies are used. Some of the more common methods include Exhaust Gas Re-circulation (EGR), Direct Water Injection (DWI), fuel-water emulsions and Selective Catalytic Reduction (SCR).

Transport Canada (TC) is committed to protection of the environment and to achieve a more sustainable transportation system. The Transportation Development Centre (TDC) of TC, in collaboration with the Emissions Research and Measurement Division (ERMD) of Environment Canada (EC) and various other partners, has been engaged in a series of projects known as the Marine Vessel Exhaust Emissions Program. The work completed includes laboratory engine tests of water injection systems and diesel-water fuel emulsions, as well as field trials on a commercial marine vessel to demonstrate the viability of a water injection system to reduce NOx emissions.

Canada's forthcoming ratification of Annex VI and successive enforcement thereof requires regulatory development (new regulations, update or modification) that must have a sound technical basis. Furthermore, it must be ensured that any regulation can be practicably achieved.

1.2 Objective

The purpose of the NOx Emission Study was to examine the underlying mechanism(s) behind the processes associated with water-based NOx reduction technologies with respect to effects on engine emissions, operation and maintenance. The intent of the study is to provide a rational framework for the reason water injection achieves NOx reduction and to develop an approach to optimize the water injection system from a knowledge-based perspective. The results will help guide future regulatory developments.

1.3 Scope

This study explored water-based NOx emission control technologies for marine diesel engines. Specifically, water injection into the charge air manifold, direct injection and fuel-water emulsions technologies were investigated. The intent of the study is to explain the processes, mechanisms, and impacts of water injection on NOx emission reduction and engine operation. The following points were addressed:

- The chemistry and thermodynamics of NOx formation and abatement.
- Process parameters (i.e. water/fuel ratio, drop size/speed, timing) that can be practically controlled and their effect on emissions.
- Side effects of NOx emission reduction, such as increased emission rates of other pollutants, reduced engine efficiency and increased fuel consumption and/or maintenance.

This study was based on a detailed literature survey of (1) charge air water injection, (2) direct injection of water into cylinder, and (3) direct injection of emulsified water/fuel into cylinder technologies. A bibliography of relevant references and a database of existing systems was generated and used as the foundation for this report.

2. REGULATIONS

There are a number of national and international regulatory organizations that propose limitations on NOx as well as other harmful emissions. The International Maritime Organization (IMO), through the International Convention for the Prevention of Pollution from Ships (MARPOL, Annex VI) regulates this on a global level. They have developed an approach to reducing green house gas (GHG) emissions, including NOx. Member countries of the IMO must therefore adhere to the regulations that they have put forth. However, some organizations have committed to adopting regulations that are more stringent. The Environmental Protection Agency (EPA) of the United States and the European Union (EU) are two such examples. These regulatory bodies have used the IMO criteria as a starting point for GHG emissions reduction but are developing certain aspects of the policy that are stricter than that of the IMO.

However, it is important to note that regulatory authorities of countries within the European Union, United States and Japan are under pressure from engine and equipment manufacturers to harmonize worldwide emissions standards. The aim is to streamline engine development and emission type approval/certification for different markets [2].

The main considerations, including similarities and differences in policy, outlined by the IMO, EU and EPA are highlighted below.

2.1 International Maritime Organization (IMO)

The IMO is a specialized agency of the UN responsible for measures to improve the safety of international shipping and to prevent marine pollution from ships. One of IMO's primary Conventions is the International Convention for the Prevention of Pollution from Ships (MARINE-POLUTION, or MARPOL) adopted on 2 November 1973. The Protocol of 1978 relating to the 1973 MARPOL was adopted at a Conference on Tanker Safety and Pollution Prevention in February 1978. As the 1973 MARPOL Convention had not yet entered into force, the 1978 MARPOL Protocol absorbed the parent Convention. The combined instrument is referred to as the International Convention for the Prevention of Marine Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78), and it entered into force on 2 October 1983 (Annexes I and II). Since coming into force the Convention has undergone many amendments, currently it includes six technical Annexes (States Parties must accept Annexes I and II, but the other Annexes are voluntary):

Annex I	Regulations for the Prevention of Pollution by Oil
Annex II	Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk
Annex III	Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form
Annex IV	Prevention of Pollution by Sewage from Ships
Annex V	Prevention of Pollution by Garbage from Ships
Annex VI	Prevention of Air Pollution from Ships

MARPOL Annex VI, Prevention of Air Pollution from Ships, was adopted September 1997 and entered into force on 19 May 2005. Member countries have one year to ratify the regulations. The Canadian national administration proposes to ratify MARPOL Annex VI in 2006/07. This will have immediate effect on ships constructed (keel laid) on or after this date. Ships constructed before this date are required to comply on the first scheduled dry-docking after this date, but in no case later than 19 May 2008.

Annex VI is applicable to all ships (as well as drilling rigs and platforms engaged in voyages) of 400 gross tons or above and requires that the ship obtain an International Air Pollution Prevention (IAPP) certificate. Engines over 130 kW are required to have an Engine International Air Pollution Prevention (EIAPP) certificate; issued to diesel engines after demonstrating compliance with NOx emission limits. Emergency diesel engines, engines installed in lifeboats or any equipment intended to be used solely in case of emergency are exempt.

Following an initial survey carried out by the Flag Administration or by a recognized organization (i.e. class society) on behalf of the Flag Administration, confirming compliance with Annex VI, an International Air Pollution Prevention (IAPP) Certificate will be issued for the ship. For ships carrying the flag of a Flag Administration that has not yet ratified Annex VI, a Certificate of Compliance may be issued.

International requirements for the prevention of pollution from air emissions are contained in Annex VI of MARPOL regulations for the Prevention of Air Pollution from Ships. The rules set limits on sulphur content in fuel, nitrogen oxide (NOx) emissions from diesel engines, emissions of volatile organic compounds (VOCs) and emissions of ozone depleting substances. Annex VI requires that diesel engines must meet NOx emission standards and be certified under the NOx Technical Code on Control of Emissions of Nitrogen Oxides from Marine Diesel Engines. The NOx Technical Code drawn up by IMO's MEPC (Marine Environment Protection Committee) defines how this is to be done.

Regulation 13 of Annex VI establishes NOx emission limits applicable to propulsion and auxiliary engines greater than 130 kW installed in ships constructed on or after January 1, 2000. The NOx emission limits are defined by a curve based on engine crankshaft speed (in revolutions per minute, rpm), as defined in Table 2.1.1 and illustrated in Figure 2.1.1.

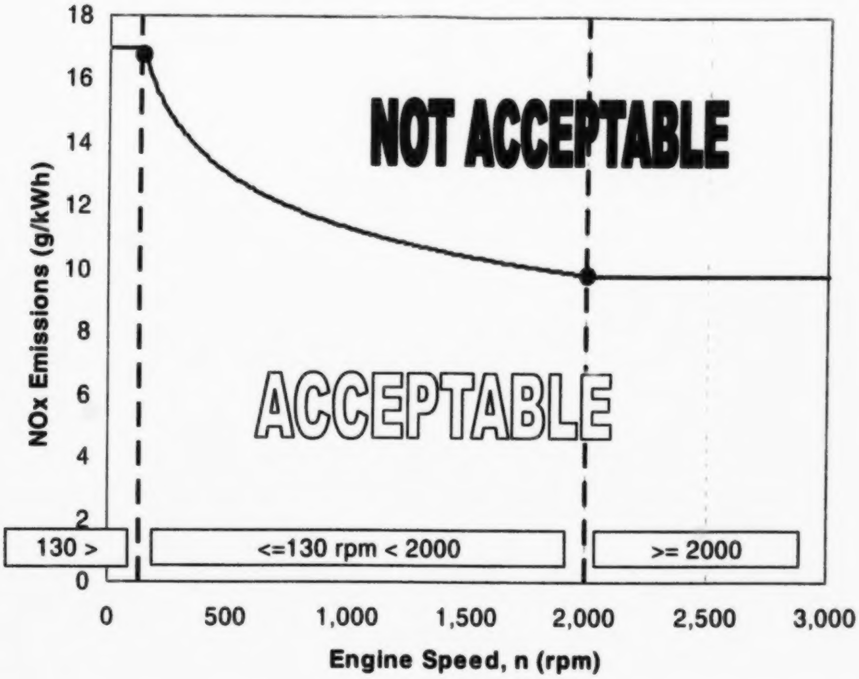
Table 2.1.1: MARPOL Annex VI NOx Emission Limits

Engine Speed (n)	NOx, [g/kWh]
$n < 130$ rpm	17.0
130 rpm $\leq n <$ 2000 rpm	$45 / n^{0.2}$
$n \geq 2000$ rpm	9.8

It is interesting to note that the lower an engine's revolutions, the higher the emission limits specified. This is to accommodate low speed (less than ~130 rpm) two stroke marine engines. Uncontrolled, two stroke engines generally have higher emissions factors than four stroke engines due to combustion characteristics i.e. higher temperatures and longer residence time of the combustion gases in the cylinder thus more time for NOx formation.

The MARPOL limits noted in Table 2.1.1 are not particularly demanding. It may be expected that IMO emission regulations will become more stringent in the future and will fall inline with other regulatory bodies (See Table 2.2.1 showing EU plans for introducing more stringent emission limits).

Figure 2.1.1: MARPOL Annex VI NOx Emission Limits



Requirements for testing, survey and certification to demonstrate engine compliance with Annex VI are set in the NOx Technical Code. The NOx Technical Code applies to all diesels with an output of 130 kW or more, except those installed in lifeboats and any equipment intended solely for emergency use. To minimize the amount of testing required, series-produced engines can be classed as family or group members and certified as such, based on satisfactory NOx emission testing of a representative parent engine. The components and data of the subsequent engines in the series are verified as conforming to those of the parent engine, as documented in its approved technical file. This file is a record of the NOx-sensitive components, settings, engine data, method of verifying the engine compliance in service and NOx emission and engine test reports.

Annex VI also requires diesel engines to carry individual certificates with regard to NOx emissions, so called Engine International Air Pollution Prevention (EIAPP) Certificates [3]. Engines are subject to:

- A pre-certification survey is normally carried out on the test bed to demonstrate it meets the NOx emission limit requirements. If the engine is found compliant, an EIAPP certificate is issued. Until ratification of Annex VI, the pre-certification survey is required for new engines supplied to ships covered by Annex VI.

- An initial survey is then carried out on board ship after the engine is installed, but before the ship enters service. This is to ensure the engine is still in conformity with the NOx emission requirements and is part of the on board survey for the issue of a ship's initial International Air Pollution Prevention (IAPP) certificate. This survey will also be required where an engine is modified or up-rated by more than 10%.

- Periodical and intermediate survey. One or more surveys will be required during the life of the IAPP certificate to verify the engine(s) remain in compliance with the NOx emission requirements.

2.2 European Union (EU)

The European Union (EU) has an environment policy that is based on the belief that high environmental standards stimulate innovation and business opportunities. To this end, they have developed a strategy to reduce atmospheric emissions from seagoing ships. The objective of this strategy, with respect to Nitrogen Oxides, is to reduce NOx emissions from ships in cases where they exceed acceptable levels and they are harmful to health and the environment. In addition to ratifying the IMO regulations outlined in MARPOL Annex VI, the European Parliament has adopted stricter emission standards for non-road engines. These standards are known as Stage III/IV and were introduced in April 2004, Table 2.2.1 outlines the criteria associated with each stage [2].

Stage III/IV limits are harmonized with the EPA Tier 3/4 standards. Furthermore, the emissions test procedure used for evaluating non-road engines was developed in cooperation with the EPA. This is a result of the pressure from engine and equipment manufacturers to standardize emissions regulations globally.

Table 2.2.1: EU Standards for Non-Road Engines

Category	Net Power [kW]	Date	CO [g/kWh]	HC [g/kWh]	NOx [g/kWh]	PM [g/kWh]
STAGE III A						
H	130 = P = 560	2006.01[a]	3.5	4 [b]		0.2
I	75 = P < 130	2007.01[a]	5	4 [b]		0.3
J	37 = P < 75	2008.01[a]	5	4.7 [b]		0.4
K	19 = P < 37	2007.01[a]	5.5	7.5 [b]		0.6
STAGE III B						
L	130 = P = 560	2011.01	3.5	0.19	2	0.025
M	75 = P < 130	2012.01	5	0.19	3.3	0.025
N	56 = P < 75	2012.01	5	0.19	3.3	0.025
P	37 = P < 56	2013.01	5	4.7[b]		0.025
STAGE IV						
Q	130 = P = 560	2014.01	3.5	0.19	0.4	0.025
R	56 = P < 130	2014.1	5	0.19	0.4	0.025

Notes:

[a] dates for constant speed engines are: 2011.01 for categories H, I and K, and 2012.01 for category J.

[b] NOx + HC combined.

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The EU is developing a system to reward environmentally proactive ships e.g. differential port fees and to provide incentives to reduce emissions beyond regulatory requirements. If the IMO has not proposed tighter international standards by 2007 the EU plans to bring forward a proposal to impose lower NOx emissions limits on engines in ocean going vessels [4].

2.3 Environmental Protection Agency (EPA)

The Environmental Protection Agency of the United States has been protecting human health and the environment since 1970. Like the EU, the EPA has adopted the regulations issued by the IMO but has used it as a foundation for a more stringent policy for marine emissions (for non-road engines).

The EPA regulation system is divided into three tiers that are meant to progressively lower emissions. Tier 1 standards are equivalent to the MARPOL Annex VI NOx limits and were voluntary when first implemented but mandatory by 2004. The Tier 2 standards for all engine sizes, which are more restrictive than Tier 1, are to be in place by 2007. Tier 3 standards for engines rated over 37 kW (50 hp) will phase-in from 2006 to 2008. The Tier 4 standards that currently exist do not apply to marine diesel engines. However, Tier 4 criteria were issued along with an 'Advance Notice of Proposed Rulemaking', which outlined the intended future emission standards for marine diesel engines [5].

Overall the EPA regulations, like those of the EU, are more restrictive than IMO MARPOL Annex VI. The EPA policy for marine engines requires better engine cooling, electronic controls and other design modifications. Also, as with the Stages of the EU system, the standards outlined in the Tier system list specific restrictions for a number of air pollutants (e.g. PM, HC, CO and NOx), while IMO does not [6]. Table 2.3.1 summarizes EPA's Tier 2 Marine Emission Standards. EPA's Tier 1 Marine Emission Standards are equivalent to the MARPOL Annex VI NOx limits.

Table 2.3.1: EPA Tier 2 Marine Emission Standard

Category	Displacement (D) [dm^3 per cylinder]	CO [g/kWh]	NOx+THC [g/kWh]	PM [g/kWh]	Date
1	Power ≥ 37 kW D < 0.9	5	7.5	0.4	2005
	0.9 ≤ D < 1.2	5	7.2	0.3	2004
	1.2 ≤ D < 2.5	5	7.2	0.2	2004
	2.5 ≤ D < 5.0	5	7.2	0.2	2007[a]
2	5.0 ≤ D < 15	5	7.8	0.27	2007[a]
	15 ≤ D < 20 Power < 3300 kW	5	8.7	0.5	2007[a]
	15 ≤ D < 20 Power ≥ 3300 kW	5	9.8	0.5	2007[a]
	20 ≤ D < 25	5	9.8	0.5	2007[a]
	25 ≤ D < 30	5	11	0.5	2007[a]

a) Tier 1 certification requirement starts in 2004. Tier 1 standards are equivalent to the MARPOL Annex VI NOx limits

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2.4 Canadian Regulations

Canada, as one of IMO's 164 Member States, currently proposes to ratify MARPOL Annex VI in 2006/07. Canada is then obliged to make provisions in its national regulatory regime to embody the Annex VI regulations. The following Acts and related regulations were developed to address environmental concerns regarding discharges from ships into waters under Canadian jurisdiction:

- Canada Shipping Act (CSA)
- Arctic Waters Pollution Prevention Act
- Fisheries Act
- Canadian Environmental Protection Act 1999 (CEPA 1999)

The Canada Shipping Act (CSA), Pollution Prevention Regulations are currently under development to align with Annex VI. Enforcement of IMO rules is made through Port State Control under the CSA.

An important consideration is that U.S. regulations often influence how Canadian regulators assess and implement regulatory requirements. U.S. regulations of particular relevance are the U.S. Environmental Protection Agency's Tier System for Emission Standards for Non-road Diesel Engines.

Other than developing and enforcing regulations for ship emissions and fuel type requirements there are additional methods that Canadian regulatory authorities may implement. Influencing operators to follow guidelines by creating differential port/fairway dues for vessels based on NOx and other emission levels has worked well in some European countries. Also, creating voluntary guidelines may prove a useful method of introducing stricter regulations for marine engine emissions. Canada has already addressed Annex VI regulations within the recently published guidelines for cruise ships [7].

3. MECHANISM OF NOx FORMATION

NOx formation in diesel engines is a very complex process and despite years of experimental research and modelling work it is still not fully understood. Much of the current understanding arises from direct measurements as well as study of flames under simplified conditions. This is then linked to the existing knowledge of diesel combustion. A great deal of this effort has focused on heavy-duty high-speed diesel engines used in on-highway equipment burning conventional light diesel fuels. However, less attention has been directed on medium and low speed diesel engines used in marine applications and even less to those operating on heavy fuels.

3.1 Diesel Combustion

Before discussing the formation of NOx, it is important to understand the Diesel combustion process. The current understanding of combustion in high speed diesel engines is described by Flynn et al. [8] and illustrated in Figure 3.1.1.

Immediately after the beginning of injection, as penetration of the fuel jet increases, more and more hot air is entrained into the jet causing its temperature to rise. As the liquid fuel is heated it vaporizes and a sheath of vaporized and heated fuel/air mixture forms around the jet's periphery and leading edge. The vaporizing fuel jet grows until about 5 crank angle degrees (0.7 milliseconds) after the start of injection when the temperature in the plume reaches approximately 750K. At these temperatures, reactions typical of the breakdown of high cetane fuels begin to occur. As these reactions take place and additional hot air is entrained into the jet, temperatures within the jet reach approximately 825K, increasing the rate of these oxidation reactions. The products of these reactions are largely C_2H_2, C_2H_4, C_3H_3 fuel fragments, CO and H_2O. Most of the energy release in these early reactions arises from the formation of water. The temperatures reached as these reactions occur are of the order of 1600-1700K. As these reaction products are formed, they are pushed aside by the penetrating jet and then re-entrained into the jet. Temperatures within the jet rise, shortening the jet and stabilizing it into a shape similar to that are shown in the last frame of Figure 3.1.1 and in more detail in Figure 3.1.2 [8, 9]. A sheath of fuel/air vapour surrounds the liquid jet, which is about 25 mm long. At about the same time, the diffusion flame begins to form around the jet's periphery. As seen in Figure 3.1.1, when starting at about 6.5 crank angle degrees After the Start of Injection (ASI), a diffusion flame sheath forms around the periphery of the cloud of partial oxidation products. These hot oxidation products then become available for aspiration into the entering jet by shear stresses in the zone 21-30 mm from the nozzle orifice.

While the above explanation is applicable to high speed diesel engines operating on light diesel distillates with high cetane numbers such as #1 and #2 diesel fuel, care must be taken in extrapolating this explanation to medium and low speed engines operating on heavy fuels. Heavy fuels have viscosities and distillation characteristics that differ significantly from those for lighter fuels. This can have a significant impact on spray formation and the ensuing combustion process. Bastenhof [10] demonstrates one effect that the difference in viscosity can have on spray formation. Under test conditions similar to those that would be experienced in a Pielstick PC2-5 engine, diesel fuel with its low viscosity produces droplet sizes that are in the order of 20-30 μm in size and that change very little as fuel temperature (and therefore viscosity) changes. However, heavy fuel oil demonstrates a much different behaviour. Droplet sizes for the heavier fuel varied from 40 μm to 120 μm and had a very strong dependence on fuel temperature. Spray development and combustion in heavy fuel engines is very dependent on the temperature of the fuel as it leaves the injector. As injector tip temperature may show variation with engine load, combustion at low load conditions with heavy fuel can be very poor. There can be very long ignition delays and high particulate emissions.

Figure 3.1.1: Combustion in High Speed Diesel Engines

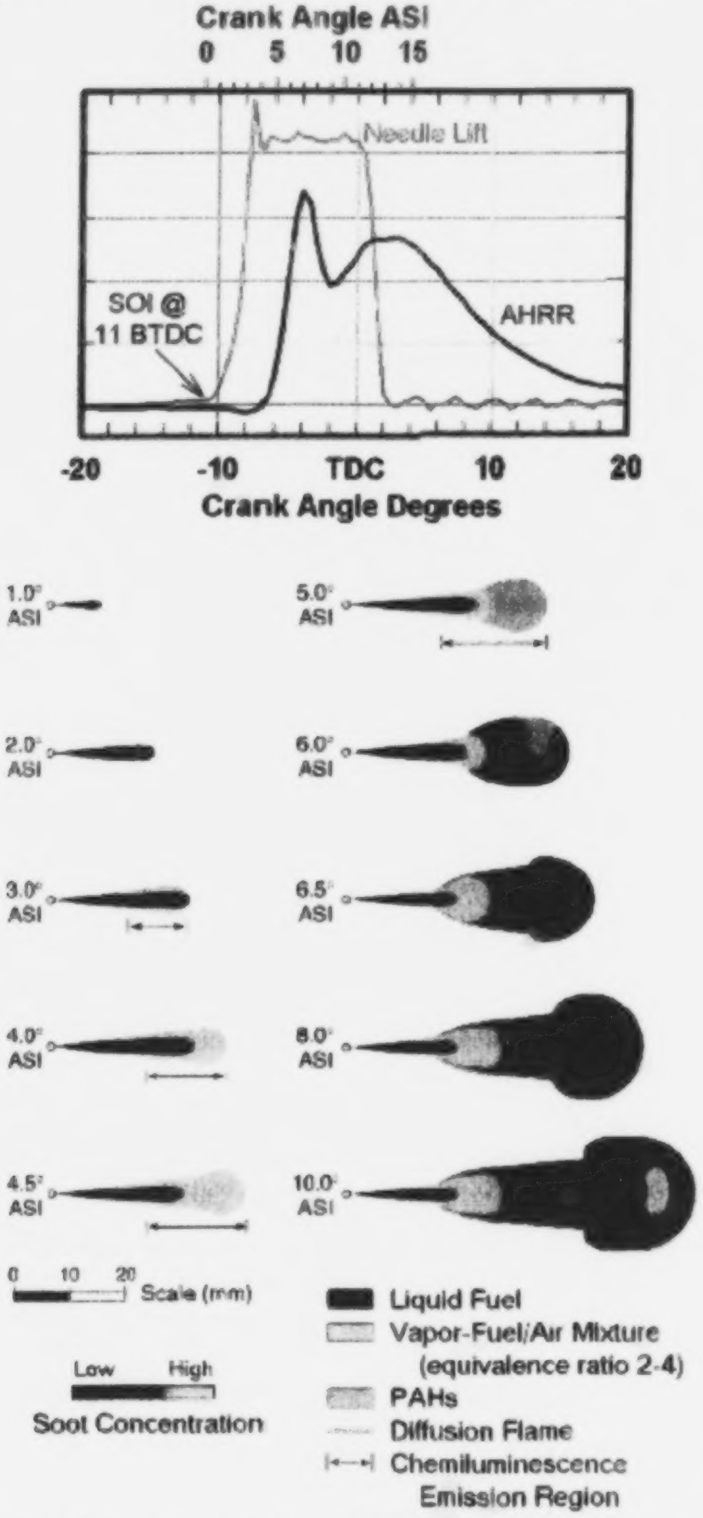

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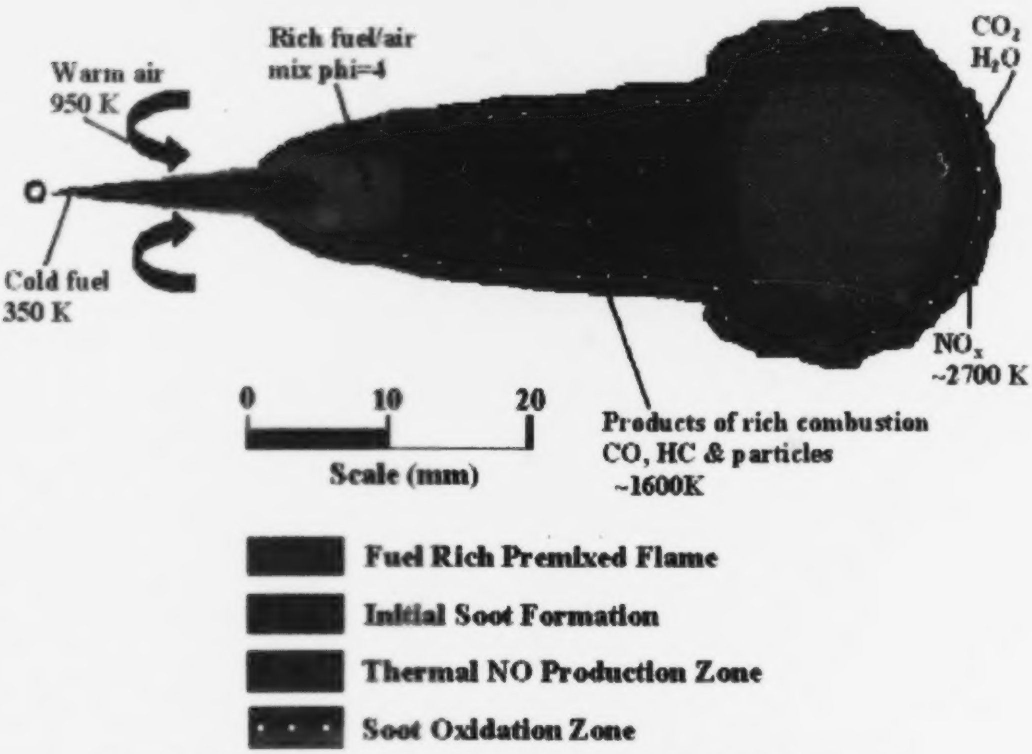
Figure 3.1.2: Conceptual Spray Combustion Model


Warm air
950 K
Rich fuel/air
mix phi=4
CO_2
H_2O
Cold fuel
350 K
NO_x
~2700 K
0
10
20
Scale (mm)
Products of rich combustion
CO, HC & particles
~1600K
Fuel Rich Premixed Flame
Initial Soot Formation
Thermal NO Production Zone
Soot Oxidation Zone

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Visualization work by Takasaki et al. [11] showed the difference in spray development between marine diesel fuel and heavy fuel oil. With marine diesel fuel, the liquid spray behaves in a fashion very similar to that described by Flynn et al. [8]. The liquid core extends a short distance from the injector and evaporates quickly and the ensuing vapour shows good mixing with the surrounding air. The liquid core with heavy fuel however, extends much further and reaches to the end of the vapour cloud to impinge strongly on the piston. Poor mixing with the surrounding air is also demonstrated. Heavy fuel oils have much higher distillation temperatures and in some cases, the air temperature in the combustion chamber can be lower than the boiling point of the highest boiling point fractions of the fuel. As a result, in addition to fuel vapour, burning of fuel droplets and even coke particles can occur [12].

The combustion process for light diesel fuels with good cetane characteristics is becoming well understood. However, combustion in diesel engines operating on heavy fuel oils has not received as much attention and is not as well understood. Sufficient evidence exists to clearly demonstrate that there are significant differences between these fuels. Light diesel fuel jets vaporize very soon after leaving the injector and the ensuing cloud of fuel vapour mixes with air in the combustion chamber and subsequently burns in a fashion as described above. Heavy fuel jets however, penetrate much further and can easily impinge on combustion chamber surfaces even in large open chamber diesel engines.

3.2 NOx Formation

There are a number of different formation mechanisms responsible for NOx in combustion processes. The relative importance of these different mechanisms is strongly affected by the temperature, pressure, flame conditions, residence time and concentrations of key reacting species. The reacting species can potentially proceed through a number of different chemical mechanisms resulting in the formation of NOx. At the temperatures greater than 2000K oxygen combines with nitrogen to form oxides of nitrogen. Initially, NO is formed, then during the gas expansion process in the cylinder a portion of the NO converts to form nitrous oxide (N_2O) and nitrogen dioxide (NO_2). The combination of NO, NO_2 and N_2O is known as NOx.

3.2.1 Thermal NO

The thermal mechanism, also known is the "extended Zeldovich mechanism", is responsible for the majority of NOx emissions from diesel engines when peak combustion temperatures exceed 2000K. Since temperatures of this magnitude are desirable to maximize engine efficiency, this mechanism has been studied extensively and is fairly well understood. The three chemical reactions that are important in this mechanism are:

$$O + N_2 = NO + N \qquad \{1\}$$

$$N + O_2 = NO + O \qquad \{2\}$$

$$N + OH = NO + H \qquad \{3\}$$

The overall reaction rate for this mechanism is slow and it is very temperature sensitive. As a consequence, thermal NO only appears in significant quantities in the post combustion. Also, the actual NO concentration from this mechanism deviates significantly from equilibrium concentrations. This gives this mechanism a very strong time dependence that is important for low speed engines.

The forward rate of reaction {1} and the reverse rates of reactions {2} and {3} have strong temperature dependencies. Therefore, this mechanism is very important at higher temperature and at air/fuel mixtures that are close to stoichiometric. Its contribution to NOx emissions is almost insignificant at temperatures below 1700K, but is strongly accelerated as temperature increases above 2000K. The temperature sensitivity of this mechanism also means that as the temperature in the combustion chamber drops during the expansion stroke, the NO concentration freezes shortly after top dead centre.

Post combustion equilibrium concentrations of O and OH are very important for this mechanism. Factors that increase or decrease the concentrations of these radicals can have a significant impact on NO from this mechanism.

3.2.2 Prompt NO

The prompt NO mechanism, also known as the "Fenimore mechanism", is very rapid and results in NO formation in the combustion zone. The most important pathway for prompt NO is initiated by the rapid reaction of hydrocarbon radicals from the fuel with molecular nitrogen, leading to the formation of amines or cyano compounds that subsequently react to form NO. The most important initiation reaction for prompt NO is:

$$CH + N_2 = HCN + N \qquad \{4\}$$

Subsequent rapid conversion to NO is strongly affected by O and OH. Prompt NO is most significant when combustion occurs at fuel concentrations higher than stoichiometry where there is a high concentration of hydrocarbon radicals to form HCN and the concentrations of O and OH are still high enough to cause the HCN to proceed to NO through the following reaction sequence:

$$HCN + O = NCO + H \quad \{5\}$$

$$NCO + H = NH + CO \quad \{6\}$$

$$NH + H = N + H_2 \quad \{7\}$$

$$N + OH = NO + H \quad \{8\}$$

The rates of these reactions are not very sensitive to temperature. Reactions are rapid and the sequence results in NO formation in the flame zone. High temperatures do not affected prompt NO to the same extent as thermal NO.

3.2.3 N_2O Pathway

Another NO formation mechanism important in combustion is the N_2O pathway. The initial reaction for this pathway is the three body reaction:

$$O + N_2 + M = N_2O + M \quad \{9\}$$

While N_2O generally reverts back to N_2, this is not always the case. Under conditions where the air-fuel ratio is lean, NO can form through either of the following two reactions:

$$N_2O + O = NO + NO \quad \{10\}$$

$$H + N_2O = NO + NH \quad \{11\}$$

This NO formation route is fuel and pressure dependent. At higher pressures and lower temperature, the three-body initiation becomes competitive with the $O + N_2$ reaction in the thermal mechanism.

3.2.4 Fuel Nitrogen

Many heavy fuel oils contain organic nitrogen bound to the fuel molecule. This nitrogen can react to form additional NO. The extent of the conversion of fuel nitrogen to NO is nearly independent of the identity of the model compound, but is strongly dependent on the local temperature and stoichiometry and on the initial level of nitrogen compound in the fuel-air mixture.

The pathway that fuel nitrogen follows to form NO depends on whether the nitrogen is bound to an aromatic ring or an amine. If the fuel nitrogen is bound to an aromatic ring, the nitrogen in the fuel forms hydrogen cyanide (HCN). In the flame, equilibrium exists for the reaction $HCN + H = CN + H_2$ and the nitrogen would form NO through a mechanism that is essentially that of prompt NO.

If however the fuel nitrogen is bound to an amine, ammonia (NH_3) would form quickly in the flame zone. In large radical pools, the NH compounds are in equilibrium:

$$NH_3 = NH_2 = NH = N \quad \{12\}$$

The important reactions for forming NO from this radical pool are:

$$NH_2 + O \rightarrow NHO + H \quad \{13\}$$

$$NH_2 + O_2 \rightarrow NHO + OH \quad \{14\}$$

$$HNO + X \rightarrow NO + XH \quad \{15\}$$

$$HNO + M \rightarrow NO + H + M \quad \{16\}$$

3.2.5 NOx in Diesel Flames

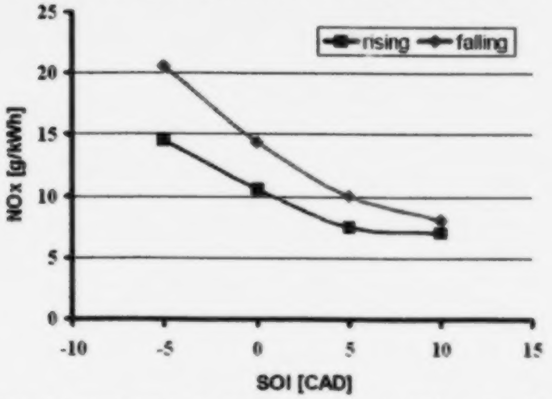
The critical flame zone in Diesel combustion for NO formation is the diffusion flame that surrounds the jet. In normal Diesel combustion, the fuel hydrocarbon radicals are broken down into fuel fragments, H_2 and CO in the partially premixed zone the core of the fuel jet. While NO can form in partially premixed flames, the temperature of this zone in Diesel engines is generally too low to result in significant NO formation. The fuel fragments, H_2 and CO from the core of the jet are the fuel that feeds the outer diffusion flame.

Under diffusion flame conditions fed with hydrocarbon fragments, H_2 and CO, the NO formation mechanisms mentioned can all play an important role. Thermal NO is especially important when peak temperatures in conditions exceed 2000K. Prompt NO will almost certainly be produced from hydrocarbon fuel fragments and its relative role would tend to increase as measures such as changes in combustion phasing are taken to lower combustion temperatures to reduce thermal NO. The importance of the N_2O mechanism under Diesel engine conditions has also been recognized [13]. Its relative importance is increased under conditions of increased turbulence [14]. It is especially important to consider the NO formed from organic fuel nitrogen in engines burning heavy fuels. Most of these fuels contain significant amounts of nitrogen. The relative importance of fuel nitrogen would increase as other measures are taken to reduce NOx formed by other mechanisms.

3.2.6 Injection Timing

Engine features that will affect the combustion chemistry can be expected to have an impact on NOx formation. This includes injection parameters such as pressure, rate shaping, orifice size and shape. For example, retarding injection reduces firing pressure, which in turn lowers peak temperature and reduces NOx (but increases fuel consumption). Figure 3.2.6.1 [9] illustrates the influence of injection timing on NOx formation. This figure plots NOx emissions vs. Start Of Injection (SOI) in Crank Angle Degrees (CAD) for rising (increasing the fuel delivery rate through the injection event) and falling (decreasing the fuel delivery rate through the injection event) injection.

Figure 3.2.6.1: Influence of Injection Rate



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Funatsu and Nagase [15] have investigated the relationship between NOx emissions and CN spectral emissions in Diesel combustion. Analysis of the prompt NO mechanism found that measures such as retarding injection timing intended to reduce NOx emissions actually increased CN spectral emissions. The implication is that, while retarding injection timing may have significant impacts on thermal NO, its impact on NO formed in the flame zone via the CN route (an equilibrium exists for the reaction $HCN + H = CN + H_2$ in the flame zone) will not necessarily be the same. Adding water to the intake air reduces both the high temperatures responsible for thermal NO and CN emissions from the flame zone.

3.3 Added Water Effects

There are generally three possible effects of adding water vapour into the combustion chamber of a diesel engine: a dilution effect, a thermal effect and a chemical effect. A vaporization effect can be included if water is added as a liquid.

Confusion can arise between the definitions of dilution effect and the thermal effect. Some definitions [16] of the thermal effect account for not only differences in specific heat capacity of the gases but also the mass of the diluent (water for example) that is present in the combustion chamber. In this case the dilution effect would only account for differences in concentration of reacting species and the role of concentration in the Arrhenius rate expression. Other definitions of thermal effect [9] only account for the specific heat capacity of the gas and include the effect of added mass of diluent in the dilution effect.

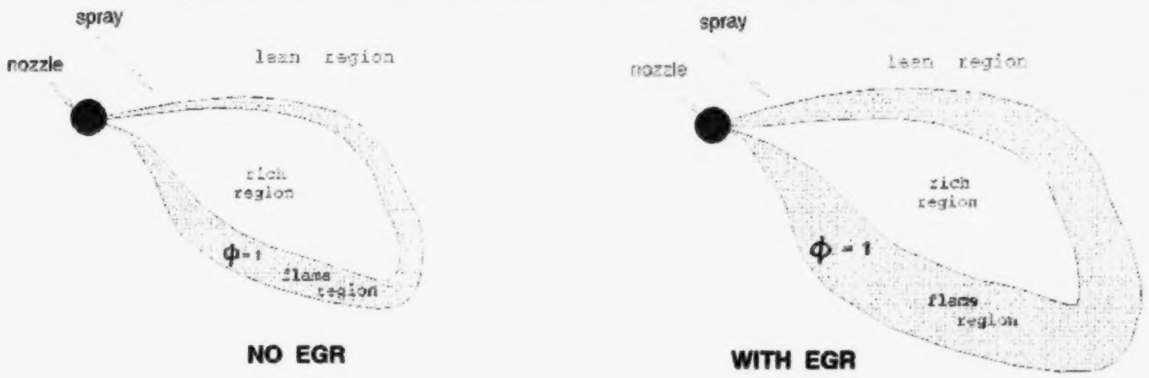
A significant body of work was carried out at Brunel University in the late 1990s to clarify the effect that dilution of the intake air by water vapour, carbon dioxide and combinations of these gases have on the combustion and emissions in a Diesel engine [16,17,18,19]. It was found that the most significant impact on NOx reduction was through a reduction in flame temperature due to the dilution effect for all gases. For water addition, the thermal effect (specific heat capacity only in this case) while smaller than the dilution effect was not insignificant and accounted for ~15% of the total NOx reduction. The chemical effect under their test conditions was small.

To clarify, the working definition of the dilution effect in the Brunel work accounted for not only differences in concentration but also included the extra mass and thus the heat capacity (the product of specific heat capacity and mass) of the 'non-oxygen' gases in the cylinder. While the total heat capacity of the inducted gases (oxygen + 'non-oxygen') in the cylinder may not have changed significantly, displacing some of the intake air with a diluent shifts more of the intake charge's total heat capacity away from oxygen and into gases that do not participate significantly in the main heat release reactions.

This is important because of the nature of diesel combustion. Measurements not only at Burnel [20] but by others [21] have confirmed that charge dilution in a diesel engine provides a major reduction in the local flame temperature. It is this reduction in local flame temperature that is primarily responsible for the decrease in NOx when water vapour or other diluents are used. This reduction in temperature is a result of the changes in the flame zone that result from differences in oxygen concentration relative to the concentration of the 'non-oxygen' gases.

The key to understanding this lies in the fact that diesel combustion is a diffusion burning process with fuel entering the reaction zone from the fuel jet and oxygen and other gases entering the reaction zone from the other side as shown in Figure 3.3.1 (simplified representation of diesel engine diffusion flame with and without Exhaust Gas Re-circulation (EGR)) [18]. The main reaction zone occurs in a region where the local oxygen and fuel ratio is essentially stoichiometric. As some of the oxygen in the inlet charge is displaced with other gases, more inert gas will be present in the combustion zone relative to oxygen and because the amount of fuel added will remain constant, the fuel will have to diffuse further and the shape and size of the flame will adjust to maintain the stoichiometric conditions in the flame zone. The added mass of non-reacting gases in the combustion zone absorbs heat and lowers the temperature in the reaction zone.

Figure 3.3.1: Diesel Engine Diffusion Flame (With and Without EGR)



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The effect of diluting with water is similar. If the quantity of fuel in the flame region is the same for both cases, the diluted case results in a broader flame region in order to provide the required oxygen for the fuel and lower flame temperatures result [20].

While the work of Ladommatos et al. [17] suggests that the chemical effect of adding water to the cylinder charge is negligible, it needs to be kept in mind that this conclusion was drawn from a high speed diesel engine operating on diesel fuel under one speed and load condition. Medium and low speed marine engines operate on a variety of fuels and can have combustion characteristics that can differ significantly from those for high speed engines. The importance of the chemical effect of diluting the charge with water under these conditions is unknown.

Water promotes the formation of OH through the reaction:

$$O + H_2O = OH + OH \qquad \{17\}$$

and inhibits OH consumption through the reaction: $OH + H_2 = H + H_2O$. This serves to reduce the concentration of O radicals – especially in the flame zone where super-equilibrium concentrations of O are present – and increases the concentration of OH [22].

The thermal NO mechanism is the most sensitive to temperature. Therefore the dilution effect on thermal NO, to the extent that it results in lower peak combustion temperatures, will be most significant. Based on the numerical simulation of coaxial jet methane/air diffusion flames, adding water from the air side is more effective at reducing peak flame temperatures than by adding the water on the fuel side [23]. A similar effect is also noted for counter-flow diffusion flames. More water can be present in the flame zone when the water is added from the airside.

The N_2O and prompt NO mechanisms are much less sensitive to temperature than the thermal mechanism. The dilution effect is important for the N_2O and Prompt NO mechanisms but not as significant as in the case of the thermal mechanisms.

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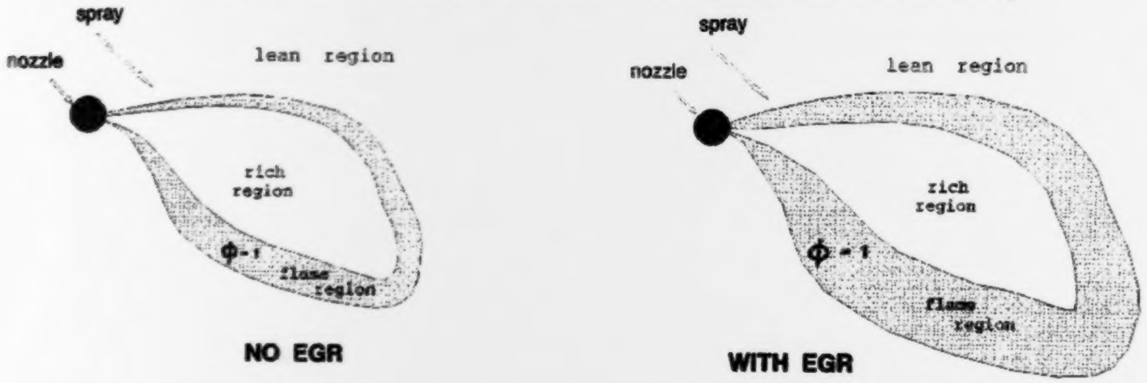

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The N_2O and prompt NO mechanisms are much less sensitive to temperature than the thermal mechanism. The dilution effect is important for the N_2O and Prompt NO mechanisms but not as significant as in the case of the thermal mechanisms.

The chemical effect of water for the prompt mechanism is mainly a result of increased OH. OH promotes the oxidation of hydrocarbon radicals and therefore inhibits the initiation reactions such as CH + N2 = HCN + N [22,15].

The chemical effect on the N_2O mechanism can arise from reductions in O radicals [24]. NO formed by this mechanism forms rapidly in the flame zone where super-equilibrium concentrations of O occur. Any reductions in flame zone levels of O will suppress the initiation reactions for these mechanisms $O + N_2 + M = N_2O + M$.

The absolute value of the super-equilibrium concentration of O in the flame zone decreases as water in the flame zone increases, however the decrease is less than the equilibrium concentration in the post flame gases [25]. This implies that the relative contribution of NO from the N_2O mechanism will increase compared to thermal NO with more water in the flame zone.

In summary, while the nature of combustion in medium and low speed diesel engines operating on fuels commonly used in marine applications will differ from high speed engines operating with on-road diesel fuel, it is expected that the mechanism of charge dilution with water to lower NOx emissions will be similar. The reduction in flame temperature due to the reduced concentration in oxygen is expected to be most important. This will be most apparent on NOx formed by the thermal mechanism.

4. NOx REDUCTION – GENERAL OVERVIEW

Methods to reduce NOx emissions may be categorized as either Primary or Secondary. Primary methods reduce NOx formation at the source in the engine and include methods such as engine tuning/modifications and water based technologies. Secondary methods reduce NOx in the exhaust gas by downstream treatment (reduction of NOx after formation in the exhaust).

Although some secondary methods are very effective, for example, Selective Catalytic Reduction (SCR) has a reduction capability of up to 95%, overall costs are typically higher. Primary methods typically have higher initial costs, usually associated with the modifications to the engine, but the overall expense is considerably less.

The effectiveness of different NOx reduction methods varies considerably. Data is often 'manufacturer claimed' and effectiveness can be dependent on the specific engine, installation and load conditions. Table 4.1 is presented to give an idea of the magnitude of potential NOx reduction feasible.

Table 4.1: NOx Reduction Methods

Method	**NOx Reduction [%]**
PRIMARY	
Delayed Fuel Injection	2-3
Reduced Scavenge Air	5
Common Rail Control	20
Exhaust Gas Re-circulation (EGR)	50
Water Cooled Rest Gas (WaCoReG)	70
Simple Charge Air Water Injection System (WIS)	30
Combustion Air Saturation System (CASS)	10-30
Humid Air Motor (HAM)	50 - 80
Direct Water Injection (DWI)	20-50
Fuel -Water Emulsions (FWE)	10-50
SECONDARY	
Selective Catalytic Reduction (SCR)	75 - 95
Wet Scrubber	15
Non-Thermal Plasma	90
Methods highlighted by shading are discussed in this report.	

The report's focus is on water based NOx reduction methods. For many of these methods, the primary mechanism of NOx reduction is a reduction in combustion temperature via the heat of vaporization of water. NOx formation occurs at very high temperatures; lower temperature combustion results in less NOx formation. For others (i.e. HAM), NOx reduction is achieved through dilution and oxygen and nitrogen starvation.

There are a variety of ways to introduce water into the system including:

- Water injection into the inlet manifold/ air intake;
- Water injection directly into the combustion chamber via a separate nozzle;
- Water injection directly into the combustion chamber via the same nozzle as fuel (stratified fuel-water-fuel injection); and
- Water injection directly into the combustion chamber via the same nozzle as fuel (premixed fuel-water emulsion).

Each of these technologies has been developed with the ultimate goal of reducing NOx emissions. However, there are pros and cons with each. Some are better than others at reducing (or at least maintaining) other harmful emissions, sustaining engine reliability and/or system installation and operating costs. Wirbeleit provides a qualitative evaluation of the four water-based technologies as outlined in Table 4.2 [26]. The author developed this table simply for qualitative comparison; [-] and [+] indicating a negative and positive effect respectively; a [--] and [++] indicating a more pronounced effect comparatively (to [-] or [+]).

Table 4.2: Evaluation of Water Based NOx Reduction Methods

	Relative NOx reduction	Effect on PM emission	Variability of Water Addition	Effect on Cold Start	Lubricating Oil dilution	Expense
Inlet manifold water injection	-	--	+	none	--	-
DWI - separate nozzle	-	--	++	none	-	--
Diesel fuel-water emulsion	+	++	--	--	-	-
Stratified diesel-water-diesel injection	++	++	++	none	none	--

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5. NOx REDUCTION - INTAKE AIR HUMIDIFICATION / WATER INJECTION

Of the different approaches for introducing water into the combustion chamber, humidifying the intake air has the potential to provide the greatest reductions in NOx. Water/fuel (W/F) ratios from 1 to 3 are possible (depending on charge air temperature) with this approach if the energy for water evaporation is provided by waste engine heat from either the exhaust or the cooling system [27].

A number of approaches for intake air humidification have been attempted. While there are some differences in the approaches, the most successful intake air humidification systems take significant steps to ensure that only water vapour enters the cylinder and that liquid water does not carry over into the cylinder and cause cylinder liner corrosion problems. In order to get high NOx reductions, this often means that the humidity of the air is near saturation as it enters the engine and that the intake manifold air temperature is as high as the engine can tolerate.

5.1 Key Parameters: Effect on Formation of Emissions and Engine Operation

A number of key parameters emerge that need to be considered to successfully apply an intake humidification / water injection system to a diesel engine, the more significant parameters are:

- temperature of the air from the point where water and air mix to the point where the humid air enters the cylinder;
- water droplet size;
- location in the intake system where the air is humidified; and
- engine load and W/F ratio.

These parameters are interrelated and any changes in one parameter will lead to corresponding changes in the others. For example, a change in engine load changes charge air pressure and temperature. Low engine loads at lower speeds can also mean longer time for NOx formation and thus higher brake specific NOx.

5.1.1 Charge Air Temperature and Pressure

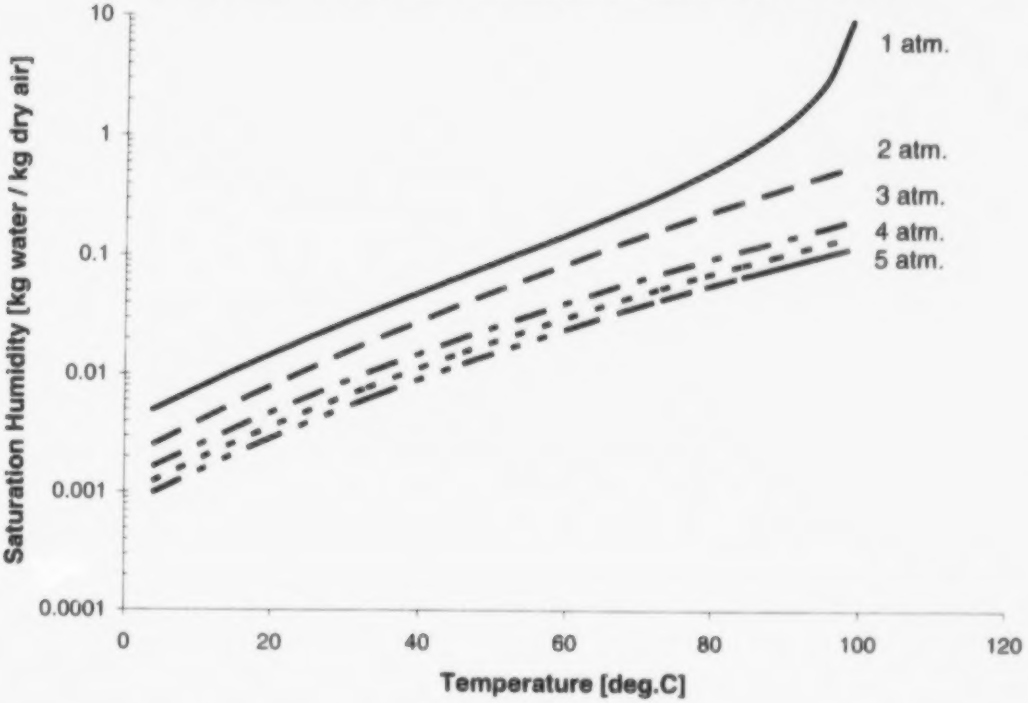
It is important to consider the overall effect of temperature and pressure on the moisture carrying capacity of air. Figure 5.1.1.1 below shows the absolute humidity of air [kg water/kg dry air] as a function of temperature for several different absolute pressures.

In general, the amount of humidity that air can hold increases exponentially (e^{aT}) with the temperature and decreases approximately inversely with pressure (1/P). For the range of temperatures and pressures considered here, an increase in temperature of about 10°C can approximately double the amount of humidity that the air can hold. The effect of pressure is not so dramatic but important nonetheless. The sensitivity to pressure decreases as pressure increases.

For the Munters HAM system and the Wärtsilä CASS that use intake manifold temperatures of 60°C and higher, Figure 5.1.1.1 implies that these systems are able to operate at humidity level greater than 50 to 80 g water/kg air. For the system that was used on the M/V *Cabot* [28] where intake manifold temperatures were as low as 24°C after humidification, the humidity ratio would be nearly 5 g/kg air. If the intake air temperature after humidification can be maintained near 40°C, humidity near 10 to 20 g water/kg air should be possible.

While new engines with advanced cylinder liner and piston technology can operate with intake air near saturation, this may not be the case for older engines [29]. Care needs to be taken when considering intake humidification for older engines to avoid cold corrosion problems.

Figure 5.1.1.1: Absolute Humidity of Moist Air at Saturation



5.1.2 Droplet Size and Evaporation

Intake air humidification is usually carried out with water sprays and relies on the evaporation of water droplets. The basic principles of droplet evaporation can be described by the "D^2 Law". While this approach does make several simplifying assumptions,[1] it does provide some insight into the droplet evaporation process and can provide guidance in implementing an intake air humidification system based on water spray.

The first consideration is the effect of droplet diameter on the time it takes for the droplet to evaporate. Figure 5.1.2.1 plots the results from the D^2 Law model. The time it takes for a droplet to evaporate varies with the square of the droplet diameter (D^2).

Gas turbines commonly use intake air humidification to provide some intake air cooling. Droplet sizes of ~10-20 μm are typical. The CASS system under development by Marioff in cooperation with Wärtsilä claims that droplets less than 200 μm are acceptable but that droplet sizes less than 50 μm would be best. The required droplet size for any given application depends on the temperature of the air in which the droplet is evaporating and the residence time available during which the droplet must evaporate. The lower the temperature available for humidification and the closer to the combustion chamber the water is introduced, the more critical it is to have small droplet sizes.

---

[1] Major assumptions include: 1) spherical symmetry (forced and natural convection are neglected); 2) the droplet is an isolated one immersed in an infinite environment; 3) heat and mass transfer in the liquid occur only because of diffusion with a moving droplet surface; 4) the process is isobaric; 5) it uses constant gas-phase transport properties.

Figure 5.1.2.2 shows the effect of ambient pressure on droplet evaporation time for a 50 μm droplet at 50°C. The effect is essentially linear: droplet evaporation time increases linearly with pressure.

Figure 5.1.2.1: Time for Droplet Evaporation in Dry Air at 1 atm and 40°C

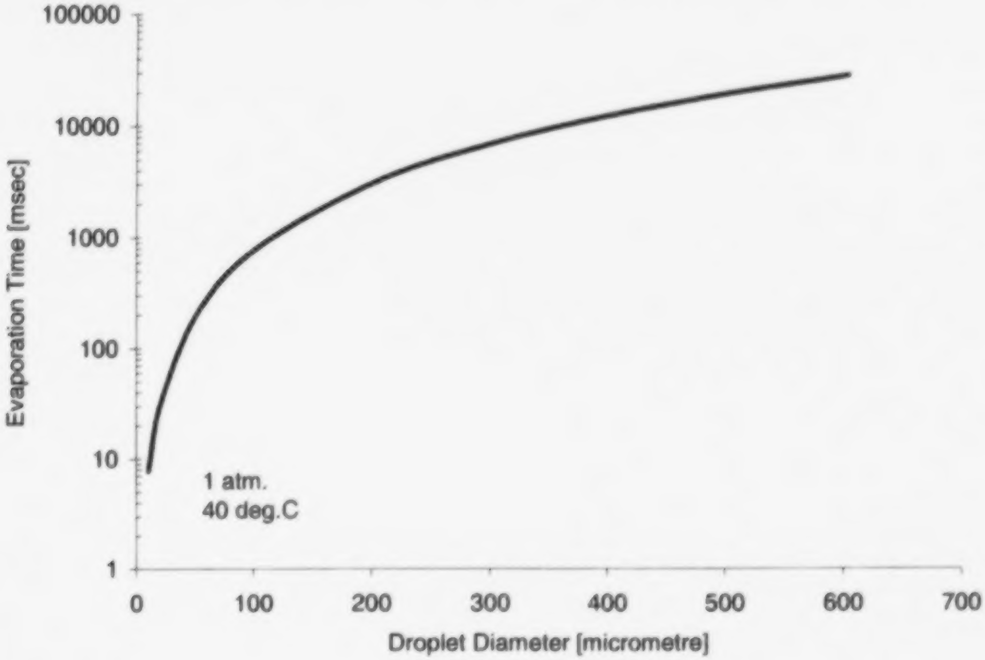


Figure 5.1.2.2: Effect of Ambient Pressure on Evaporation Time (a 50 μm droplet at 50°C)

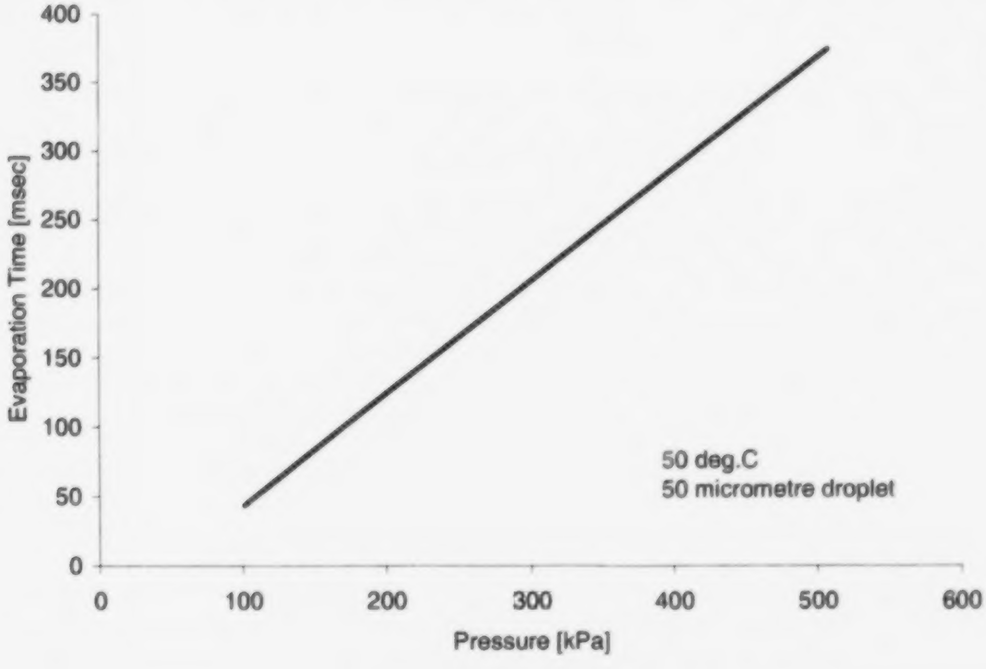
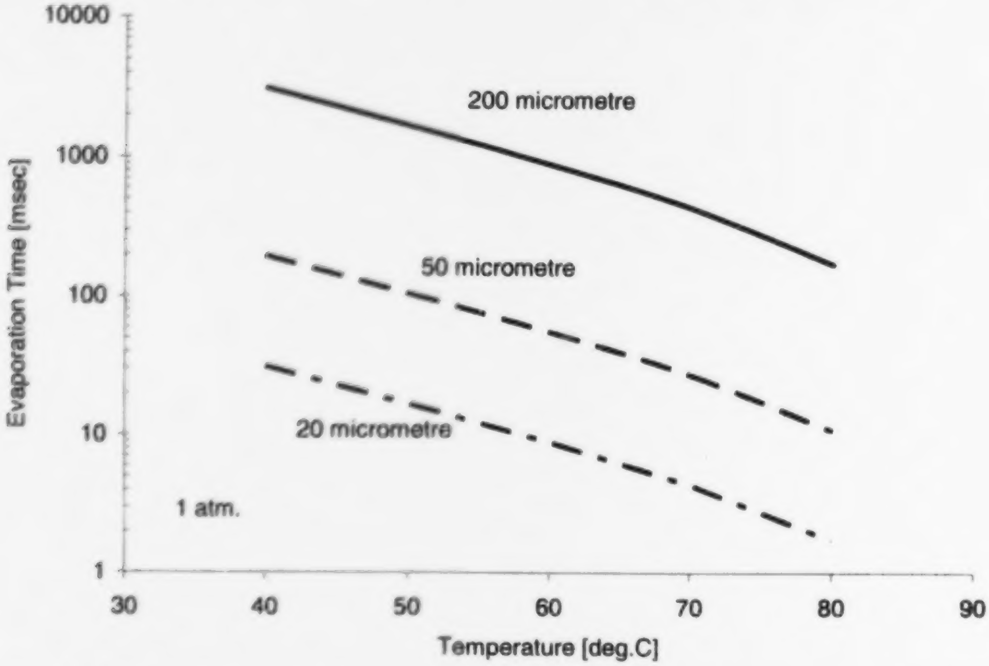


Figure 5.1.2.3 shows the effect of temperature on droplet evaporation time. The evaporation time for any given droplet size varies approximately exponentially with temperature (e^{-aT}). A decrease in temperature of about 10°C can approximately double the time that it takes for a droplet to evaporate. Clearly temperature is critical to getting good droplet evaporation.

Figure 5.1.2.3: Effect of Temperature on Droplet Evaporation Time



In many cases, the temperature at the outlet of the intake compressor can be in excess of 100°C. Depending on the pressure, droplets could be injected into an air stream that is above the boiling point of water and droplet evaporation would be much faster than that predicted by the D^2 Law.

5.1.3 Location of Water Injection

The best location for injection in the intake system is determined by two guiding factors. The best choice for any a given application will maximize the amount of humidity that can be added to the intake air to give the highest reduction of NOx and achieve almost complete evaporation of the water droplets before the air enters the cylinder. Good evaporation is critical in many applications in order to avoid cylinder liner corrosion problems, to ensure even distribution of water to the cylinders and to ensure that combustion and emissions are not adversely affected.

In most diesel engines, there are essentially three options for the location of intake air Humidification:

- before the compressor;
- after the compressor but before the intercooler; and
- after the intercooler.

Humidification before the intake air compressor avoids operating the humidification equipment at pressure. This would be a consideration if a humidification tower is used as in the HAM approach.

Unless the air is pre-heated, the temperature before the compressor is low and while the low temperature is somewhat compensated for by the low pressure, good evaporation can be a problem. Poor evaporation, while improving the efficiency of the compression process, can lead to compressor damage. If proper precautions are taken, humidification of intake air is possible before the compressor. It does offer the advantage of long residence times (longer intake duct run) and good mixing of air and humidity. This would help ensure good an even distribution of humidity to all cylinders of the engine.

Another option is to humidify the air immediately after the compressor. Temperatures here can often be well over 100°C and in some cases, above the boiling point of water. This would provide excellent droplet evaporation. The humidification process could provide a cooling effect as well so that it would be possible and/or desirable to reduce the coolant flow to the intercooler in order to maintain a temperature in the intake manifold that maximizes the amount of humidity in the air and at the same time, avoids engine operating problems. In some cases, it may even be possible to eliminate the intercooler altogether and rely solely on the evaporation of water to maintain acceptable intake manifold temperatures. A negative effect of humidification before the intercooler is coalescence and increased condensate in the intercooler.

The third possible location for air humidification is after the intercooler. This is not usually the best choice because the temperature of the air has been lowered by the intercooler and the humidification potential is not only smaller but adding water here further reduces the air temperature and therefore even further reduces the humidification potential. The second problem is that not only are droplet evaporation times much longer here than before the intercooler, the time available for the droplet to evaporate is shortened as well because of the proximity to the combustion chamber.

The effect of choice of the location of water injection into the intake system is critical. The temperatures and pressures at the point of humidification and downstream to the point where the humid air enters the combustion chamber determine the amount of water that can be added to the intake air while avoiding liquid carryover into the cylinders.

5.1.4 Engine Load and Water/Fuel Ratio

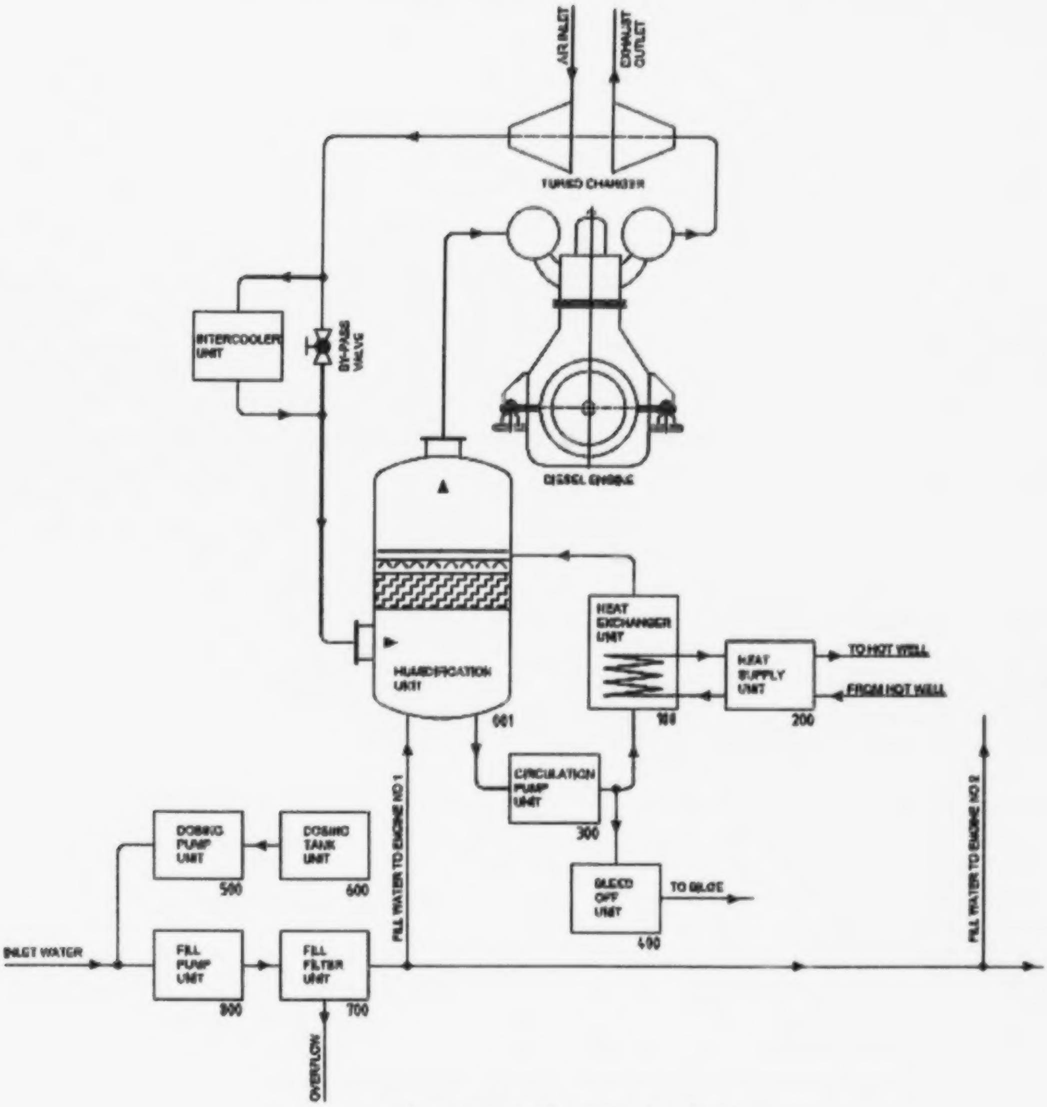
Brake specific (g/kWh) NOx emissions reduce with engine load regardless of the W/F ratio used (true of operation with no intake air humidification / water injection system). Low engine loads and lower engine speeds mean longer residence time for NOx formation and thus higher brake specific NOx emissions. Changes in engine load result in changes in the charge air temperature and pressure. Thus the effects discussed in Section 5.1.1 and 5.1.2 may be considered a function of engine load also. The same may be said of the W/F ratio; see also Section 3.3.

5.2 Proprietary Systems

5.2.1 Munters

The basic design and principles of the Munters Humid Air Motor (HAM) is described in one of their patents [30]. Figure 5.2.1.1 shows a diagrammatic of the HAM. A humidification tower is placed between the intake air compressor and the engine. Water that is pre-heated with waste engine heat is sprayed from nozzles at the top of the column into the air flow entering from the bottom. An amount of water far in excess of that required to saturate the air is supplied. Only 5% to 10% of the water sprayed into the tower evaporates [27]. Water that does not evaporate into the air is collected at the bottom and re-circulated.

Figure 5.2.1.1: Munters Humid Air Motor (HAM) System


AIR INLET
EXHAUST OUTLET
TURBO CHARGER
INTERCOOLER UNIT
BY-PASS VALVE
DIESEL ENGINE
HUMIDIFICATION UNIT
001
HEAT EXCHANGER UNIT
100
HEAT SUPPLY UNIT
200
TO HOT WELL
FROM HOT WELL
CIRCULATION PUMP UNIT
300
BLEED OFF UNIT
400
TO BILGE
DOSING PUMP UNIT
500
DOSING TANK UNIT
600
INLET WATER
FILL PUMP UNIT
800
FILL FILTER UNIT
700
OVERFLOW
FILL WATER TO ENGINE NO 1
FILL WATER TO ENGINE NO 2

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Supplying excess heated water accomplishes two things. It makes the system self-regulating. The amount of humidity added to the intake air, assuming that the tower is sufficiently sized to allow saturation of the air, is governed by the temperature and pressure of the air during the humidification process. The excess heated water also provides heat for the evaporation process. This minimizes the temperature drop of the air in the humidification tower ensuring that the humidity of the air stays as high as possible. Also by supplying excess water that has been pre-heated from waste engine heat, use of steam that would otherwise need to be generated from higher temperature heat sources can be avoided.

Fitting a vertical humidification tower on board a ship can be a problem. To overcome this, a horizontal humidification chamber has also been developed [31]. Effective humidification is achieved in the horizontal arrangement when the water is introduced either in a cross flow or parallel flow manner. Packing blocks in the humidifier also ensure that the contact time between air and water is longer. A droplet separator at the outlet keeps liquid water out of the engine. Salt water can be used to humidify the air because in the evaporation process, the salt is left behind in the water that falls to the bottom of the humidification tower. Depending on specific details of the application, an intercooler may not be needed or at the very least, the cooling carried out by the intercooler would need to be moderated to keep the humidity as high as possible and to avoid liquid water condensation after the humidifier.

The HAM process designed by Munters Euroform GmbH was first bench tested on a MAN B&W 3V40/50 prototype 4 stroke medium speed diesel engine in the research and development facilities of S.E.M.T. Pielstick in-service verification was carried out in co- operation with Viking Line on one engine (12 PC2.6, 5,750 kW) onboard the RoRo ferry "Mariella" operating in the Baltic Sea. The HAM system was installed on main engine No. 1 in the summer of 1999 [32]. NOx reductions of 60% were claimed with a final certification value of 4.4 g/kWh NOx [33]. The humidification vessel is 4 m long, 1.4 m in diameter and has 3 humidifier stages which humidify and cool the air from approximately 160°C at the outlet of the compressor down to approximately 65-70°C. The air reaches about 98 % relative humidity which corresponds to an absolute humidity in the range of 60 to 80 g water/kg dry air. Sea water is used and re-circulated until the salt content increases by about 6% [34].

While the HAM system does reduce combustion temperatures, any resulting loss of efficiency is made up by an increase of work from the exhaust turbine. A higher mass flow through the turbine results without an increase in compression work when water is introduced after the intake compressor. An increase in intake air pressure can result [27].

Work at the Lulea University of Technology in Sweden on an 11 litre 6 cylinder Scania high speed diesel engine examined the effect of the HAM on emissions [35]. The average NOx reduction was 51% on the ECE R-49 13-mode cycle. Intake humidity from 32 to 53 g water/kg dry air were achieved. W/F ratios were in the range of 1 to 4.5. Adjustments in the amount of heat transferred from the engine cooling system to the humidification water allowed NOx reduction levels to be adjusted. It was found that the particulate matter particles emitted from the engine increased for all load and speed conditions except idle when the HAM was used. No change in mean particle diameter was observed that could be attributed to the HAM system. Some increase in unburned hydrocarbons and CO were also observed.

5.2.2 Wärtsilä

Stork Werkspoor first developed an intake air humidification system in the 1980s. At the time, problems with liquid water carryover into the cylinder and the associated cold corrosion problems kept the amount of water that could be added to the air quite low. Improvements in cylinder liner and piston technology for newer engines have improved the ability of these engines to tolerate humidity in the combustion air, and Wärtsilä has again take up the development of this system.

Unlike the Munters' HAM system which claims a self-regulating behaviour, the Wärtsilä approach requires careful control of the water flow to achieve the proper humidification. This requires measurement of intake manifold temperature, humidity and in some cases, pressure. The system also requires pure water; seawater would need to be treated first before it could be used. The Wärtsilä approach also uses multiple stages of humidification with heating or cooling in between the stages as needed; humidification of air after the compressor [36].

The operation of the heat exchangers in the air intake system in either heating or cooling mode depends on the engine load condition and the level of NOx reduction required. For the example, the intake air requires heat from the engine's cooling system at all but the highest loads to reach the level of saturation required for adequate NOx reductions [36]. Intake air cooling is required only under conditions when both the engine load is high and when the required NOx reductions are less severe. If high NOx reductions are required at high load, air heating may still be required. At low load operation, sufficient heat may not be available from the engine's cooling system to supply enough heat to the intake air to reach the required level of saturation and other steps such as direct water injection or a fuel/water emulsion may be needed in addition to intake air saturation to reduce NOx at the low load conditions [37].

During the year 2000, Marioff, a developer of water mist systems for fire suppression, started to develop the Combustion Air Saturation System (CASS). The key to this system development is the spray nozzle and control system. Air and water in varying ratios are supplied to the nozzle providing water droplet sizes around 50 to 200 µm and W/F ratios from 0.5 to 2.5. The air/water ratio supplied to the nozzle is varied so that the water droplet size is a function of engine load with the smallest droplet sizes produced when the engine load is low and good evaporation is more difficult [38]. Early in 2001, a press release was issued that stated that Marioff and Wärtsilä had formed a partnership. During 2001 and early 2002, full-scale engine tests were carried out at Wärtsilä in Finland. Reduction of NOx to less than 3 g/kWh was claimed at the time for starting values of 10-15 g/kWh. Current claims are ~50% NOx reduction at W/F ~ 2.0 and saturated air at 50-90°C [39].

5.2.3 Prototype Retrofit Systems

Prototype intake air water injection systems have been developed by M.A. Turbo [40,41,42,43,44] and the Transportation Development Centre (TDC) [45,46]. Readers are directed to Section 8 of this report for details on these systems and test datasets. Both systems are intended for retrofit to existing engines. Unlike HAM and CASS which are sophisticated designs intended to input gaseous water (vapour) into the cylinder, the M.A. Turbo and TDC systems introduce atomized liquid water into the intake air supply (which may or may not be vapourized when entering the cylinder).

5.2.4 System Comparison

The TDC system used in the 2005 M/V Cabot trials is the most refined of the prototype systems reviewed. A comparison is made between this system and the Munters HAM and Wärtsilä's CASS systems in Table 5.2.4.1.

Table 5.2.4.1: Humidified Air Systems: HAM, CASS and TDC Systems

	HAM	CASS	TDC
Intake manifold temperature	65-70°C	70-90°C	24°C
Water	heated sea water	fresh water	fresh water
Saturation humidity	60 – 80 g/kg dry air	80 – 160 g/kg dry air	5 g/kg dry air
Water/fuel	~3.00	~2.00	~ 0.70
Intercooler operation	humidification tower cools charge	intake air is heated at all but the highest load conditions to maximized intake air humidity	no optimization carried out
Injection location	after compressor	after compressor	after intercooler
BSNOx @ W/F=0	11-16 g/kWh	10-15 g/kWh	~12.5 g/kWh
NOx reduction	60-70%	60%	~30%

The purpose of comparison is simply to highlight differences (NOx reduction and the system parameters where this reduction achieved) between intake air water injection (TDC multipoint system) and intake air humidification (CASS, HAM) systems.

It should be noted that the data for the TDC system is the best result achieved during limited testing in 2005. A more detailed summary of these tests and results are made in Section 8.7 and 8.8.3. System modification to allow higher W/F ratios or installation on a different engine may well produce higher NOx reduction.

5.3 Optimization

The maximum NOx reductions that can be achieved varies with the application and the engineering effort put into system design. System design should maximize the amount of humidity the air can hold while avoiding cold corrosion problems associated with liquid water carryover into the cylinder and adverse effects associated with changes in intake manifold air temperature. For the systems that claim NOx reductions of 50% or more, the engine and intake humidification processes are treated as one system and are engineered to provide high levels of intake air humidity. For the two cases discussed, Munters' HAM and Wärtsilä's CASS, the required humidity can only be achieved by an approach that will provide final intake manifold temperatures above 60°C. For the simpler approaches represented by the M.A. Turbo and TDC prototype systems, the NOx reductions are more modest. While some conditions provided reductions ~30%, the average reductions were in the range of 10 to 20%.

5.4 Cold Corrosion

In any combustion environment where sulphur is present, the major sulphur product will be SO_2. However, a small amount of SO_3 will also form; on the order of a few percent of the SO_2. SO_3 has a very high affinity for water and at temperatures less than 500°C it forms sulphuric acid. At higher temperatures the sulphuric acid dissociates into SO_3 and water. With residual fuel oils, vanadium pentoxide from vanadium in the fuel can further enhance the formation of SO_3.

Sulphuric acid corrosion, often referred to as cold corrosion, has been a significant problem in marine engines since high sulphur residual oils have been used as a fuel and it was a significant problem with early attempts at intake air humidification; it is also a problem with low-sulphur fuels [47]. Sulphuric acid has a dew point temperature that is quite high; depending on pressure and the strength of the acid, it can be well over 200°C as shown in Figure 5.4.1 [48]. The lowest temperature in the cylinder is usually located on the cylinder liner and is usually in the range of temperatures where acid condensation occurs. It is therefore on the liner that sulphuric acid corrosion problems arise.

Sulphuric acid dew point increases as the amount of water vapour in the gas mixture increases as shown in Figure 5.4.2 [20]. It is for this reason that it is a major concern when introducing extra water into the cylinder. Acid attack is a major cause of sudden and severe wear in marine engines [49]. The major engine manufacturers go to great lengths to design their engines to minimize this problem. The effect depends not only on acid concentrations but also on the amount of acid solution present on the liner wall [50]. The phase behaviour of sulphuric acid is such that the strength of the liquid phase is dependent on the temperature of the surface on which it condenses. The strength of the acid increases as the temperature of the condensing surface increases.

Lower liner wall temperature leads to the condensation of more dilute acid on the liner wall. When small amounts of aqueous acid solution are present, the hydrodynamic lubrication layer is interrupted but does not break down completely [50]. Under these conditions, dilute acid solutions are the most problematic because they corrode and weaken the matrix of the cast iron. Hard particles are left protruding which then break off and act as abrasive particles. Diesel soot can further exasperate the problem and provide additional abrasive particles and which leads to very high rates of wear [51]. As the wall temperature increases, the sulphuric acid becomes more concentrated. This stronger acid attacks the hard phase instead and still leads to high wear. At still higher temperatures, the sulphuric acid is even more concentrated and there is less attack of the hard phases and running behaviour is good. Under these conditions, the acid forms a protective layer on the metal that acts as a solid lubricant.

As the amount of aqueous acid solution increases, the hydrodynamic lubrication layer breaks down completely, a protective layer is not able to form and wear rate increases dramatically [50].

While it may not be necessary or even possible to completely prevent the condensation of some sulphuric acid on the cylinder liner, great care must be taken to ensure that any water based NOx control strategies do not contribute to the problem. The most important considerations include:

- Liquid water must not be allowed to contact the cylinder liner. The major engine manufacturers take great care to avoid liquid water in the cylinder [47,49]. This can cause a number of problems. While small amounts of strong acid solutions can actually be acceptable, introducing liquid water on the liner can dilute these strong acid solutions. The resulting dilute acid solutions can lead to sudden and severe wear. Introducing liquid water will not only dilute the acid but will also increase the amount of aqueous phase on the liner and lead to a break-down of the hydrodynamic lubrication layer and very high wear rates.
- Humidifying the intake air increases the dew point of sulphuric acid and can lead to more acid condensing on the cylinder liner. Intake humidity levels need to take into account the temperatures of the cylinder liner at all conditions under which it is applied in order to avoid cold corrosion issues

Figure 5.4.1: Sulphuric Acid Dew Point Curves Based on Fuel Sulphur

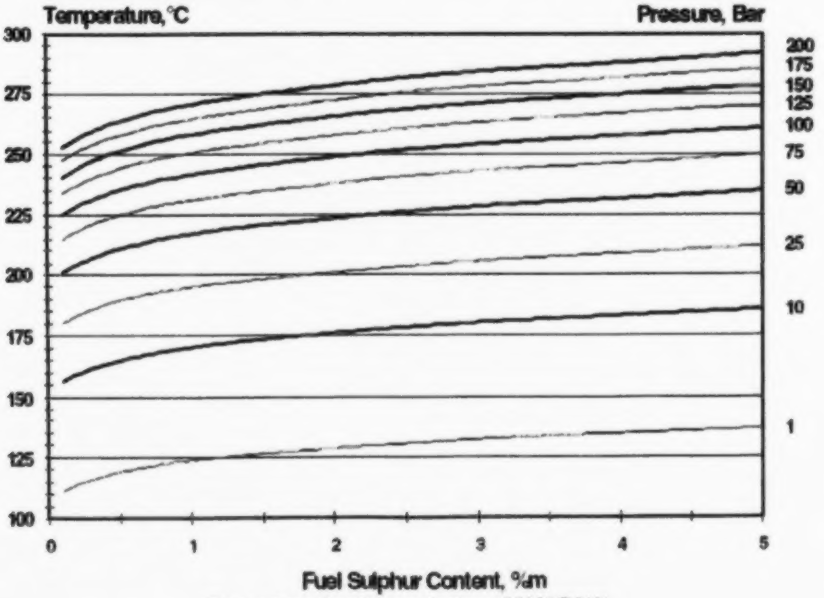

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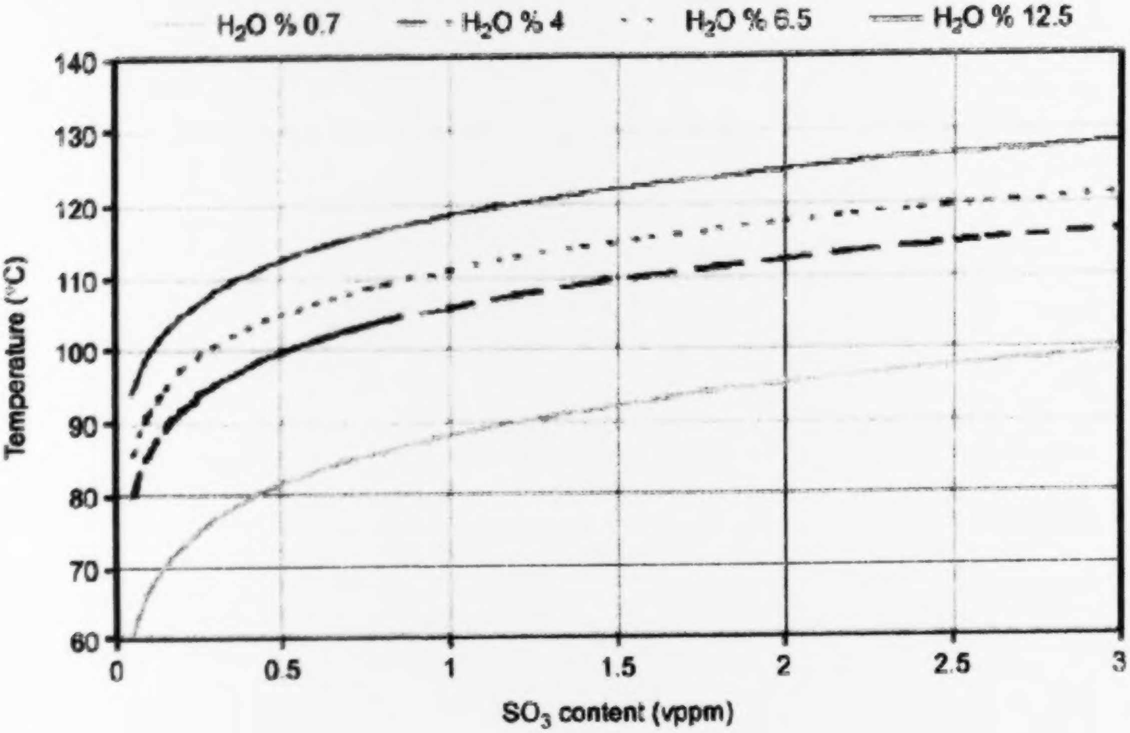
Figure 5.4.2: Dewpoint Behaviour of SO3 at Various Water Vapour Concentrations



Notes: *Formula:* $Tdew_{SO_3} = 1000/\{2.276 - 0.0294\ln(P_{H_2O}) - 0.0858*\ln(P_{SO_3}) + 0.0062*\ln(P_{H_2O}*P_{SO_3})\}$ with pressures (P) in atmosphere

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6. NOx REDUCTION - DIRECT IN-CYLINDER INJECTION

This method of NOx reduction can be carried out with two slightly different variations (1) by injecting water directly into the cylinder head via a separate nozzle, or (2) by alternating fuel and water through a specially designed nozzle. Both of these techniques for adding water are based on the same fundamental concept: injecting water into the system at the combustion cylinder reduces high peak temperatures, which in turn reduces NOx formation.

The primary benefit of injecting water directly into the cylinder through a separate nozzle is that both the amount of water and the timing that the water is injected are variable and can be controlled separately from the fuel. Similarly, the amount of water injected in sequence with fuel from a single nozzle can be varied although the timing of injection is dependent on the W/F ratio. In general, these methods allow for substantial amounts of water to be added to the system, which can, in turn, lead to large reductions in NOx emissions. Another attribute of direct water injection into the cylinder is that liquid water can usually be directed towards the flame (combustion zone) more efficiently. The water typically evaporates upon injection, which helps keep liquid water away from the wall as well as create a more homogenous fuel air mixture.

As with other water based NOx reduction methods, reduction of NOx emissions may be accompanied by increases in other emissions such as smoke, THC and PM. A practical concern with direct injection (with a high specific water consumption rate) for the ship owner/operator may be the increased amount of on-board storage space required for the injection water and the associated weight. Cost may also be a concern, while the cost of operating such a system may be low, the initial investment can be high due to engine design changes necessary as well as the cost of special nozzles. The lifetime of water injection nozzles is short [52].

6.1 Key Parameters: Effect on Formation of Emissions and Engine Operation

The parameter that has the most effect on NOx emissions from diesel engines fitted with direct water injection systems is the amount of water injected. However, there are also a variety of other parameters that can have a substantial effect on not just NOx, but smoke, HC and PM. Many of these variables are related to the conditions under which the water is injected, i.e. injection timing and injection location as well as nozzle flow/spray. The load at which the engine is running can also directly influence the emissions and engine operation. Parameters such as these, in relation to their effects on emissions (mainly NOx, but also smoke, PM and THC) and the operation of the engine, are discussed.

6.1.1 Water/Fuel Ratio

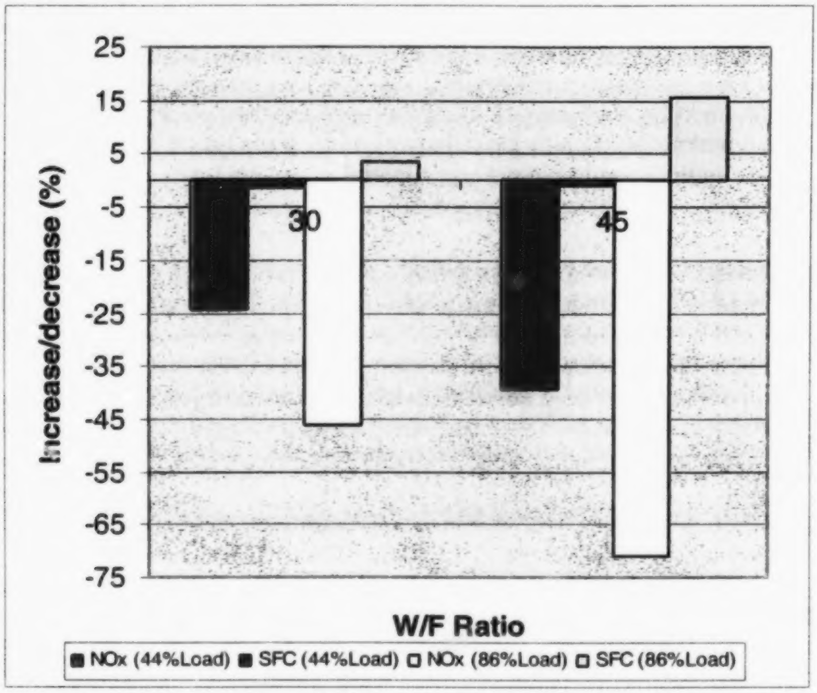
NOx formation occurs at very high temperatures. The key is to reduce highest temperatures at locations where they prevail for the longest periods of time, typically the flame zone. The addition of water is thought to help reduce combustion chamber temperatures through the heat of vaporization of water and its dilution effect as discussed in the section on NOx formation.

A range of W/F ratios can be applied to assess the impact of water on NOx emissions, as well as other emissions such as smoke, THC and PM. As there is an increase in the quantity of water injected into the system there is a proportional reduction in NOx. Typically, the relationship is linear and direct water injection allows for NOx emissions reduction of approximately one percent for each one percent increase of the W/F ratio [53].

Alternatively, an excess of water can have also negative impact on emissions. While it may cause a decrease in NOx, the large quantity of water can contribute to lower temperatures throughout the entire combustion chamber, which may lead to increased amounts of soot, THC and PM.

A study [54] analyzing the effect of increased W/F ratio on a stratified fuel-water injection system demonstrates that as W/F ratios increase NOx values decrease, this relationship is true for different engine loads. However, Specific Fuel Consumption (SFC) increases (or decreases less) as the W/F ratio is increased as shown in Figure 6.1.1.1.

Figure 6.1.1.1: The Effect of Water/Fuel Ratio and Load on NOx and SFC



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Kohketsu [55] also studied stratified fuel-water injection. Results indicate that NOx reduction is directly proportional to the relative amount of water injection but not directly dependent on engine speed and load.

6.1.2 Engine Load

As can be seen in Figure 6.1.1.1 the engine load can also have a significant effect on parameters such as NOx emissions and specific fuel consumption. This plot demonstrates that while NOx reduction is achieved at both 44% and 86% of the engine's full load, there is a greater reduction at the higher load (and the higher W/F ratio). At the lower load there is a slight decrease in specific fuel consumption as water is introduced, however there is a substantial increase in specific fuel consumption associated with the greater load.

6.1.3 Injection Timing

One of the major benefits of direct water injection as compared to other methods of NOx emissions reduction, such as emulsions, is that the timing for the injection of water can be different than the fuel injection timing.

As stated, the formation of NOx is reduced as the combustion temperature decreases. As water is added to the cylinder the flame zone is cooled and there is a decrease in NOx. The rate, thus extent, of cooling is directly related to injection timing. If the water injection is too early the whole cylinder, rather than just an isolated region, may become cooled. Although the system may experience more NOx reduction due to the extra cooling, it is possible that combustion and oxidation may not be complete which can result in increased soot levels. Also, if the temperature is lowered too early in the process there can be increased ignition delay and engine noise. On the other hand, if the water is injected into the system much later, then the result is an increase in fuel consumption.

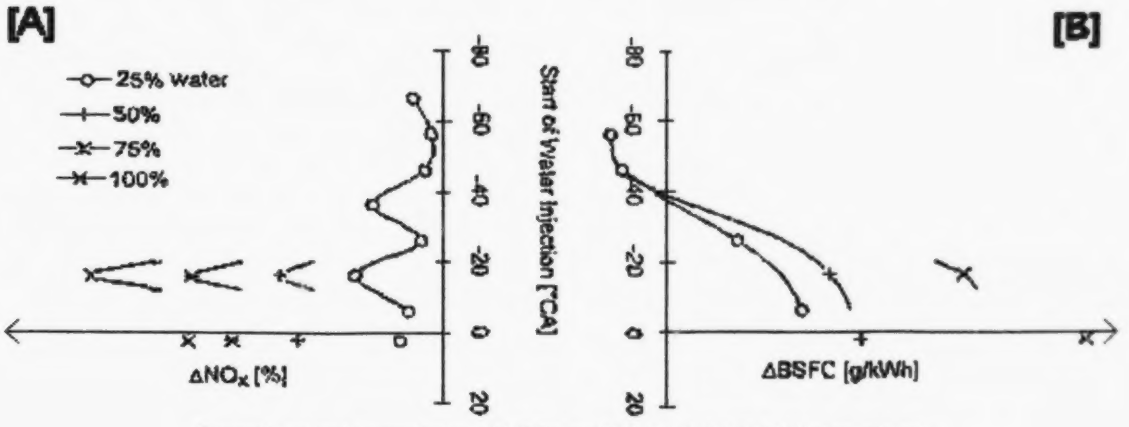
Geist [56] shows the effect timing has on NOx emissions (Figure 6.1.3.1 [A]) and on BSFC (Figure 6.1.3.1 [B]). The engine being evaluated is equipped with direct water injection (tandem injector with independent control off water and fuel injection); Sulzer 4RTX54 low speed diesel.

Timing is essential in balancing the desired NOx reduction with a limited increase in other emissions and fuel consumption. Ideally, water should be injected late during the compression stroke or in parallel with fuel. This will prevent excessive cooling and ensure that evaporation is complete and that there is no water (liquid) build up on the cylinder wall.

For stratified direct injection, where the fluids are typically injected in the order fuel-water-fuel, the timing of the injection, and thus NOx reduction, is dependent on the volume of pre-injected fuel. The amount of fuel initially injected will dictate whether the water injection is classified as early or late. Wirbeleit [26] found that, like direct water inject from a separate nozzle, if the water injection is early, NOx decreases but PM decreases and if it is late, NOx reduction is not as significant and PM still increases slightly. It was found that the optimum timing involves an intermediate volume of pre-injected fuel that allows for considerable NOx reduction without increasing PM emissions or compromising fuel consumption substantially.

In one study [55], a naturally aspirated direct injection diesel engine with stratified (fuel) water injection was evaluated. For all three injection timings tested, at a constant medium speed and a constant high load, an increase in the amount of water injected caused a corresponding decrease in NOx emissions. There was also a decrease in smoke, up to a W/F ratio of 20% and an increase in fuel consumption after the W/F ratio reached 20%. For greater fuel injection timings there is a noticeable increase in HC as the W/F ratio is increased.

Figure 6.1.3.1: Influence of Fuel Injection Timing



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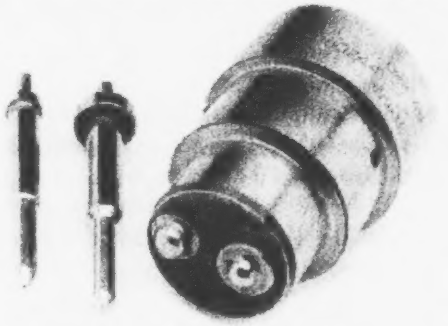
6.1.4 Injection Location

As previously stated, injection timing of the added water is most beneficial when in parallel with fuel injection. NOx reduction can be facilitated further if the location of water injection is carefully chosen. The water can be added to the system either in a separate nozzle located in the cylinder head as close as possible to the fuel nozzle or directly through the same nozzle as the fuel (as in stratified injection).

Engineering a system with separate, yet closely placed, injection nozzles would be best facilitated using a twin nozzle. This type of nozzle can integrate both the fuel injector and the water injector into a single nozzle holder while maintaining separate controls for each. There are a number of these nozzles that are similar in their duel feed capabilities. These nozzles may be referred to as twin, tandem or combined. When the fuel and water are injected in close proximity (in parallel) higher accuracy is obtained in targeting the flame zone for better cooling and the combustion process results in lower NOx and PM emissions as well as optimum fuel consumption. Figure 6.1.4.1 illustrates the type of nozzle used by Wärtsilä for direct water injection [39].

Figure 6.1.4.1: Combined Nozzle Used by Wärtsilä for DWI



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Another location to add water into the cylinder is through the fuel injection nozzle. Water and fuel are alternately added to the system but they are not mixed (as in a fuel-water emulsion) until just before the actual injection event.

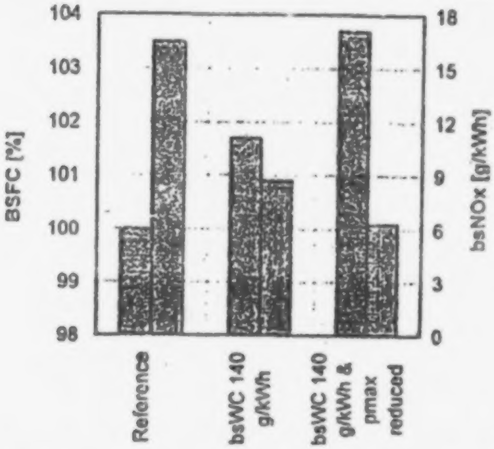
Stratified (fuel-water-fuel) direct injection into the cylinder yields results that are often slightly better than that of typical direct water injection (where fuel and water are separate). The liquid water is inserted close to the flame and away from the cylinder wall. With stratified injection it is easier to cool the flame zone directly rather than cool the entire combustion chamber. This allows for high NOx reduction without compromising other values such as fuel consumption and emissions like HC and CO. This arrangement can also minimize negative impact on overall engine reliability in that a poorly placed nozzle may over-cool the combustion chamber which may lead to ignition delay, engine knocking and incomplete combustion.

Figure 6.1.4.2 demonstrates the NOx reduction associated with a Sulzer 4RTX54 low speed diesel engine equipped with water injection (through a separate nozzle) as well as retarded fuel injection. Approximately 140 g/kWh of water is injected into the system [56].

Injection location is an important factor for many types of engines. Experimental work conducted on an indirect injection (IDI) diesel engine [57] showed that effects of water injection are more significant when water is injected into the swirl chamber, as opposed to the main chamber. At optimum timing there were reductions in NOx and smoke and the fuel consumption was maintained.

The only compromise was a slight increase in HC. Overall the results were more favourable than those based on injection into the main chamber.

Figure 6.1.4.2: NOx and BSFC due to Direct Water Injection



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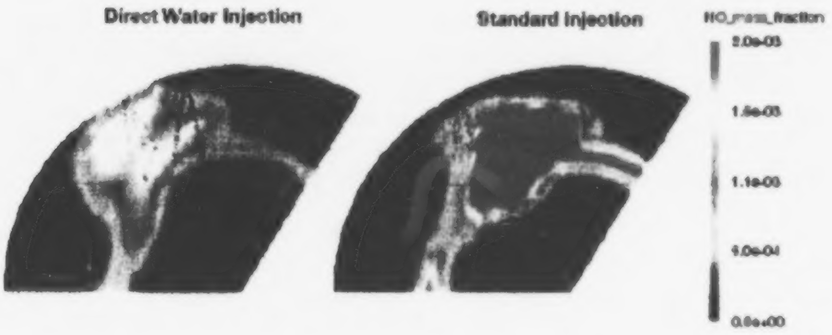
6.1.5 Nozzle Flow/Spray Distribution

The type of nozzle used for injecting the water into the system directly affects the flow of water and its spray distribution within the chamber. This will in turn affect the temperature and then the actual amount of NOx reduction.

As with location, the type of nozzle used can effect the NOx emissions as well as other emissions and parameters, in the way that it directs the spray of water. If the spray is projected to the region of highest temperature NOx reduction will be possible without compromising fuel consumption and other parameters. However, if the whole cylinder becomes cooled then PM and smoke emissions may increase and engine reliability may deteriorate. Figure 6.1.5.1 illustrates a computational fluid dynamics (CFD) simulation of the combustion process with and without direct water injection. The levels of NOx, indicated by the colours, show that the water is sprayed directly into the area of NOx concentration [58].

Figure 6.1.5.1: Distribution of NOx Levels in the Combustion Region



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In stratified direct water injection the fuel and water may experience some mixing at the injector needle area of the nozzle just prior to entering the cylinder. At pre-injection this small amount of water in the fuel spray may cause problems. If the water is biased toward the front of the spray event the pre-injection fuel may be reduced in temperature due to the evaporation of the water, which can lead to ignition delay. Fortunately the centre and the width of the spray distribution of water can be adjusted to minimize problems such as ignition delay [54].

6.2 Proprietary Systems

Direct water injection has been investigated as a legitimate NOx emission reduction technology for over 20 years. Currently there are systems that are commercially viable as the demand for NOx reduction engines increased due to stricter regulations. The cruise ship industry is a prime example of this; to promote fleets as 'environmentally friendly' action must be taken to reduce harmful NOx emissions, as well as smoke and PM.

6.2.1 Wärtsilä

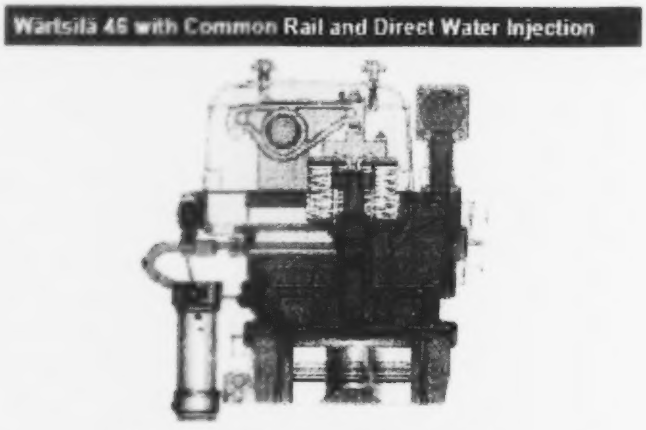
Wärtsilä has been developing the direct water injection (DWI) technology since the early 1980s. This technology was chosen for a number of reasons. In the beginning it was recognized that there were limited adverse effects on injection equipment reliability, the setup was fairly simple and the system was comparatively cheap. Wärtsilä pursued this technology and throughout the years there has been extensive research and development activity, which has included a considerable amount of field testing.

Current DWI systems by Wärtsilä boast NOx emission reduction of 50-60% (without adversely effecting power output), which translates to 4-6 g/kWh of NOx (for Marine Diesel Oil) and 5-7 g/kWh (for Heavy Fuel Oil). The system typically operates at a W/F ratio of 0.40 to 0.70. The Wärtsilä technique for DWI also allows for water shut-off, as the water system is controlled separately from the fuel, so that the engine can be operated with or without water injection. Wärtsilä claims that both investment and operational costs are low and that space requirements for the system is minimal, allowing for easy installation [39]. Wärtsilä engines that incorporate DWI technology that are currently commercially available are:

- Wärtsilä 46
- Wärtsilä Vasa 32
- Wärtsilä 38
- Wärtsilä 32
- Sulzer ZA40

Wärtsilä's current version DWI system has a water injector located at the side of the cylinder head. The purpose of this setup is to allow for common rail injection in the central injector. A schematic of this engine is displayed in Figure 6.2.1.1 [39]. This engine is dubbed the EnviroEngine as it combines common rail technology with a direct water injection system to enhance NOx reduction while reducing smoke. This engine was the result of a partnership between Wärtsilä and Carnival Cruise Lines. Its origins go back to 2000 when these companies decided to develop a more environmentally friendly marine diesel engine for use in the cruise industry.

Figure 6.2.1.1: Wärtsilä 46 Engine with both Common Rail and DWI



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The EnviroEngine uses electronically controlled, common rail fuel injection to provide optimum combustion over the entire load range. The result is no visible smoke at any load and when starting or during transient load changes. The direct water injection, which is also electronically controlled, can reduce NOx emissions to values as low as 6 g/kWh. These engines were first introduced on new build orders but due to the significant environmental advantage many vessels already under construction, and some existing vessels, underwent conversions.

6.2.2 Mitsubishi Heavy Industries

Mitsubishi has worked on stratified direct water injection for many years. Although this technology is not thought to be as main stream as direct water injection with separate nozzles, the stratified (fuel-water-fuel) technology is becoming recognized as commercially feasible and advancements are being made.

One of the earlier concepts considered, developed in 1992, was a change-over valve to inject fuel and water alternatively. The purpose was to develop a system where the fuel and water could be added through a single injection valve without affecting the condition of the fuel [59].

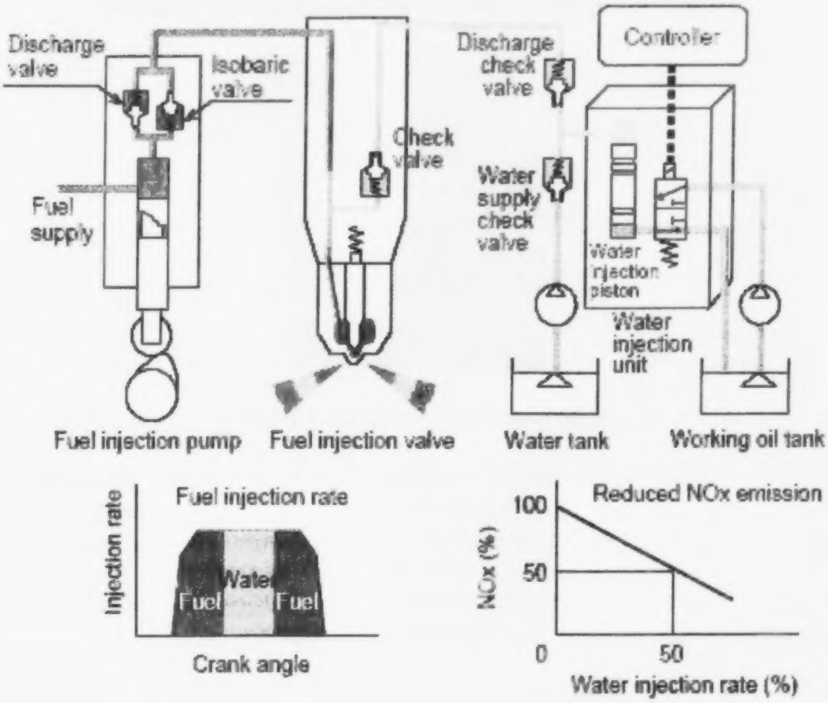
A more recent development, in 2002, is a fuel/water injection system that allows for water injection control with high accuracy, fairly simple control, reasonable cost and substantial NOx reduction. This system uses the pressures of the water and fuel, respectively, to control flow [60].

Their current system claims that it is possible to reduce NOx by up to 50%. Figure 6.2.2.1 illustrates this system [61]. Mitsubishi continues developments of this technology with refinement of methods for operating a two type fluid (fuel / water) injection capable of more precise fluid injection quantity and timing [62].

6.3 Optimization

Experimental and theoretical evidence indicate that stratified (fuel-water-fuel) DWI technology holds the most promise for NOx reduction without increasing other harmful emissions or compromising fuel efficiency and the operation of the engine.

Figure 6.2.2.1: Mitsubishi Heavy Industries Stratified WIS


Discharge valve
Isobaric valve
Check valve
Fuel supply
Discharge check valve
Controller
Water supply check valve
Water injection piston
Water injection unit
Fuel injection pump
Fuel injection valve
Water tank
Working oil tank
Injection rate
Fuel injection rate
Water
Fuel
Fuel
Crank angle
100
50
0
NOx (%)
Reduced NOx emission
50
Water injection rate (%)

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Stratified injection is advantageous over injection a separate water nozzle in that it allows for a more precise spray of water. It has the benefits associated with fuel emulsions without the hindrances on engine operations such as delayed ignition and knocking. There is also more control over the volume of water they can be injected into the system. The major drawback of stratified direct water injection is that the system design is quite expensive as it involves a complicated nozzle and considerable adjustment to the existing system. For this reason, direct water injection using a separate nozzle is often the choice of the ship owner/ operator in refitting an engine for NOx reduction capabilities.

7. NOx REDUCTION – FUEL-WATER EMULSIFICATION

This method of NOx reduction involves injecting a fuel-water emulsion into the combustion chamber. The water is added to the fuel prior to injection and the emulsion is injected through the fuel nozzle. Again, this technique for adding water is based on the principle that injecting water into the system at the combustion cylinder reduces NOx emissions by reducing high peak temperatures.

NOx reductions using fuel-water emulsions can be significant; approximately 1% NOx reduction is achieved for every 1% increase in the W/F ratio increase (for lower values). As with stratified direct water injection, the water is placed directly in the combustion region. NOx reduction may be contributed to not only the effective direction of the water towards the flame/combustion zone but also due to improved atomization of fuel-water emulsions and mixing that occurs prior to combustion. Other parameters such as smoke and fuel consumption are also favourable for emulsions. Smoke can be effectively reduced and fuel consumption is not adversely effected for emulsions that contain no more than 30% water [52].

Fuel-water emulsion systems can have a cost advantage over other systems, as they do not require elaborate design changes to the engine (modifying existing fuel line as opposed to installing separate injection water system). Operational costs are low as the only major requirement to the system is the water addition (although there may be storage space and weight concerns with the carriage of emulsion water onboard).

The main disadvantage of using fuel emulsion technology to reduce NOx emissions is that there is a limit to the amount of water that can be added to the system. For fuels emulsified with water there is always the inherent risk that there may be an excess of water injected into the cylinder either too early or too late in the combustion process. This can cause cooling of the entire cylinder, which may lead to increased ignition delay, engine noise and retarded (or incomplete) combustion. Another disadvantage is that engine operation at low loads and at stops and starts are sometimes hindered. As with other water based NOx reduction methods, maintenance issues such as cold corrosion may also arise.

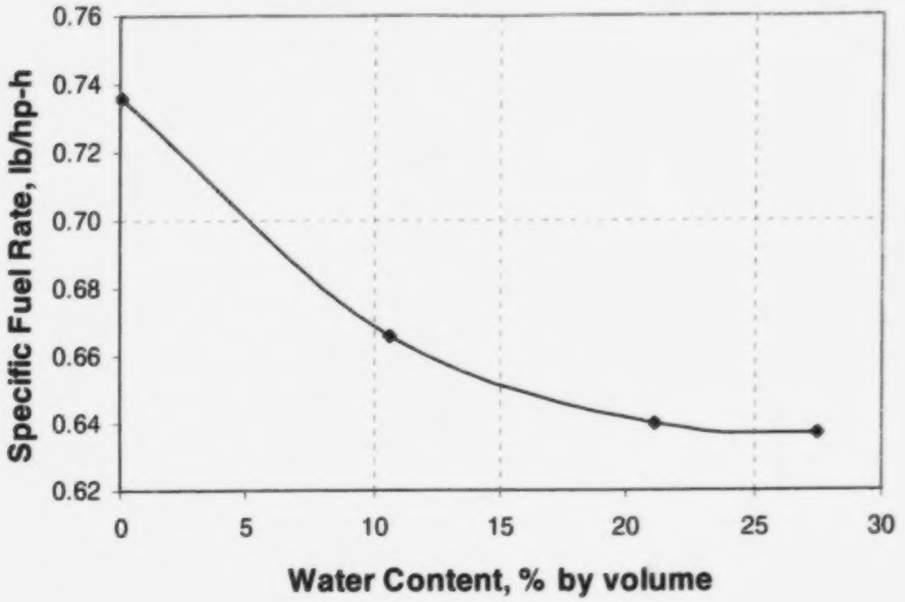
7.1 Key Parameters: Effect on Formation of Emissions and Engine Operation

The engine emissions and operation of marine diesel engines that use fuel-water emulsions are influenced by many parameters. As with the other water based technologies, the W/F ratio has the most effect on the system. However, emissions such as NOx, smoke, HC, PM and overall engine performance, including fuel consumption, are also effected by other parameters. Nozzle Hole Diameter, Engine Load and Fuel Quality, with respect to their effect on formation of emissions and engine operation, are also discussed briefly.

7.1.1 Water/Fuel Ratio

At low W/F ratios, NOx emissions decrease linearly with added water. There is approximately 1% NOx reduction for every 1% increase in W/F ratio. Bertola [63] describes the results of an experiment on a heavy-duty four stroke high speed diesel engine with common rail injection. For the case where the W/F ratio was 0.30, NOx reductions of 27% were experienced. Smoke was also reduced. However, the added water caused CO emissions to increase slightly and THC emissions to increase by about 25% over the baseline reference. Fuel emulsification can result in significant reductions in fuel consumption (maximum benefit requires proper injection timing). Figure 7.1.1.1 shows the effect of water on specific fuel rate for water to fuel rations up to 0.30 [64].

Figure 7.1.1.1: Influence of Water on Specific Fuel Rate



Nakajima [65] also found that an increase in W/F ratio resulted in reduced NOx concentrations. This reduction, to some degree, was present regardless of nozzle characteristics, engine operating performance and the type of fuel used. The maximum NOx reduction reached was approximately 60%, at a W/F ratio of 0.60.

The addition of water also increases the premixed combustion. This may have a positive or a negative effect. The premixing improves atomization and aids in combustion. However the increased amount of water present in the mixture often results in an extension of ignition delay, which may cause higher engine noise levels and retarded combustion and therefore impede NOx reduction.

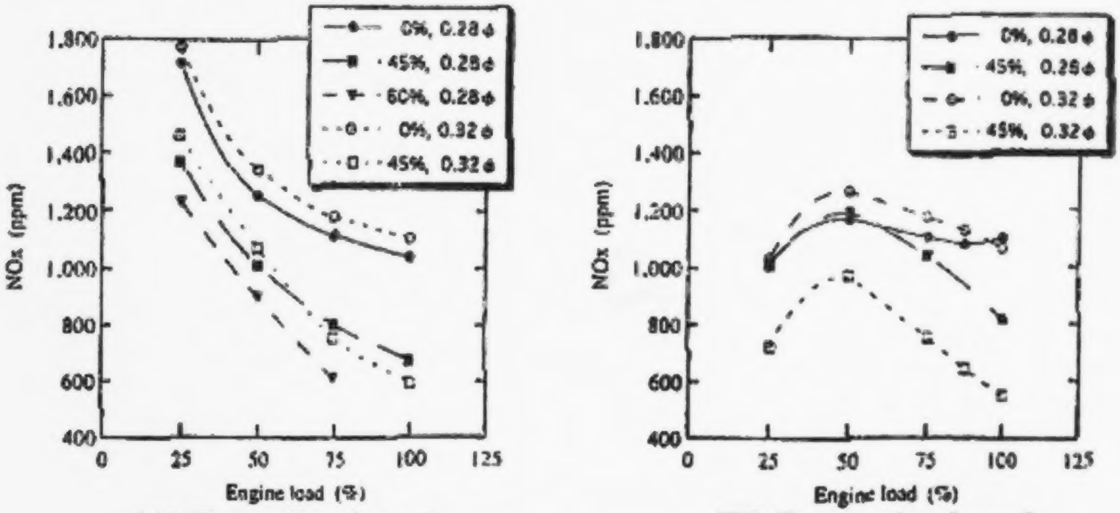
7.1.2 Nozzle Hole Diameter

Theory indicates that a smaller diameter nozzle hole would decrease NOx through effective atomization of the fuel droplet. As well, smaller particles are thought to have less of a negative effect on efficiency. Fuel-water emulsion testing, preformed by Wärtsilä on a W6L46CR engine, showed that micro-emulsion gives overall better results than traditional emulsions that have larger water droplets [29].

7.1.3 Engine Load

The work conducted by Nakajima [65] demonstrates that as load increases there is generally a decrease in NOx emissions. This is consistent regardless of the amount of water added or the nozzle diameter. However, the load for generator performance experiences a different pattern. There is an increase in NOx with increase in engine load to a maximum at approximately 50% engine load. There is then a decrease in NOx for the larger engine loads- a trend similar to the engine load for propeller performance. These relationships are illustrated in Figure 7.1.3.1 [65].

Figure 7.1.3.1: NOx Emissions from MDO for Engine Load



[A] Propeller Load **[B] Generator Load**

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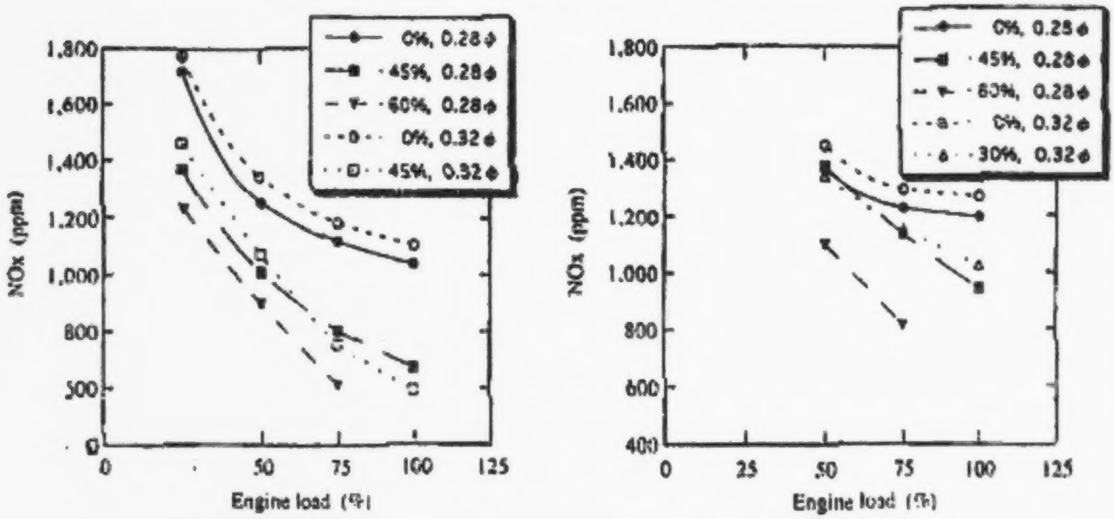
7.1.4 Fuel Quality

The type of fuel used in conjunction with the water does have an impact on the NOx emissions. Water emulsified MDO showed better reduction capabilities than emulsified HFO for similar engine loads, W/F ratios and nozzle size. Figure 7.1.4.1 highlights the differences in NOx emissions for MDO and HFO for the engine load of the propeller [65].

Figure 7.1.4.1: NOx Emissions for a Propeller Load



[A] MDO **[B] MFO**

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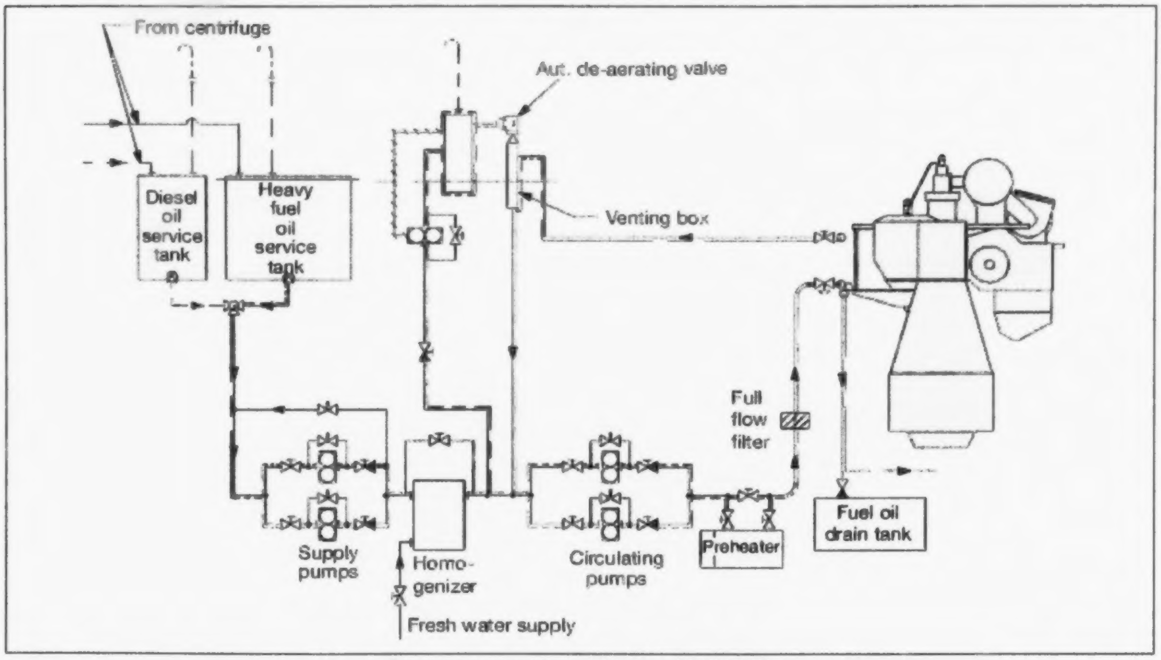
7.2 Proprietary Systems

As with direct water injection, fuel-water emulsions have been targeted for extensive research and development as a viable NOx emission reduction technology for more than 20 years. In fact, the first tests (on petrol engines) go back as far as the 1950s. Increasingly strict NOx emissions regulations around the world have brought many new designs to the forefront and there are a number of fuel water emulsion systems currently available on the market. This technology is recognized as being as practical as most of the systems in operation are successful in reducing NOx emissions without compromising engine reliability.

7.2.1 MAN B&W

MAN B&W began developing water-in-fuel emulsions as a method of reducing NOx emissions in the early 1980s. Since then they have designed a number of slow speed and medium speed engines equipped with fuel-water emulsions. Between 2000 and 2003 there were four vessels that entered service equipped with fuel-water emulsion technology. Figure 7.2.1.1 illustrates a fuel-water emulsion system with a pressurised fuel oil system and homogenizer [32].

Figure 7.2.1.1: Sample of a Fuel Oil System with Homogenizer



Reproduced with permission: MAN B&W

Through practical experience as well as research, design considerations for the MAN B&W fuel water emulsion systems have been developed [66]. For example, it is recommended that after the emulsification process the water droplets should be no larger than 5 μm. This will allow for optimum spray conditions. Also, if the engine uses diesel oil additives, to stabilize the emulsion, might be required. Another consideration is the type of water used. It must be distilled and amounts of salts must be controlled. Otherwise the system may experience leaks due to reactions such as corrosion and fouling due to build up. Fresh water (from a fresh water generator) presents the best choice of water type for a fuel-water emulsion. One other factor in designing a fuel-water emulsion system is that if HFO is used it has a tendency to increase in viscosity when water is added to it. In order to

maintain a viscosity of 10-15 cSt at the engine inlet the temperature may need to be increased (to a maximum of 170ºC at 50% water) or the fuel oil loop pressure may need to be raised.
MAN B&W has a number of engines equipped with fuel-water emulsion systems. There has been extensive work developing fuel-water emulsion technology for four-stroke engines. After a considerable amount of testing on various engines (including 1L 24/30, 1L 32/40, 6L 40/54, 48/60's and 58/64's) a vessel was finally put into service equipped with a fuel-water emulsion system. In June 2000 the MS Finnmaster, a RoRo vessel travelling between Great Britain and Finland, was commissioned as the first vessel entered into commercial service with a MAN B&W four-stroke with fuel-water emulsion. This ship operates in the Baltic and North Seas and has many ports of call. The amount of time spent in harbours prompted the operator to seek a NOx reducing system. This ship is the first of a series of 4 that are propelled with a MAN B&W 12V 48/60 engine.

The fuel water emulsion system used in this vessel is comprised of two modules. The fuel water emulsion water injection module filters, heat and pressurizes fresh water before delivering it to the mixing tank. The other module, the fuel water emulsion booster, is similar to a standard fuel module except that it includes a homogenizer. The water is brought into the fuel system at the booster module prior to entering the mixing tank. Throughout operation of the system the water dosage is adjusted depending on the engine output.

This MAN B&W fuel water emulsion system, as tested in the vessel MS Finnmaster, was found to have no negative effects on operating data and fuel consumption. Also, engine components were found to be in good condition and lubricating oil was found to be normal upon inspection after 3582 operating hours (approximately 2000 with fuel water emulsion) [52].

7.2.2 Wärtsilä

For many years fuel water emulsion technology was not widely used by Wärtsilä. It was found that introducing water into the fuel of a traditional diesel engine raised issues such as cavitation problems in the injection equipment, additional camshaft loading, and limitations with the injection pump and different nozzle requirements. However, in recent years it has it was observed that common-rail injection technology can alleviate most problems associated with fuel-water emulsions. This factor, in conjunction with the use of more efficient emulsifiers (creating micro-emulsions), has increased Wärtsilä's interest in developing fuel water emulsion technology.

Fuel-water emulsion testing, preformed by Wärtsilä on a W6L46CR engine, showed that micro-emulsion gives overall better results than traditional emulsions that have larger water droplets [29]. The Wärtsilä fuel-water emulsion tests had water droplets that were 5-10 μm at a pressure of 20bar and temperature of 70-90°C. The influence of the emulsion on emissions such as nitrogen oxides, carbon oxides and smoke, as well as fuel consumption was generally positive.

7.3 Optimization

Fuel-water emulsion technology is an attractive method for NOx emissions reduction primarily due to its simplicity in system installation and operation. Emulsions, especially micro-emulsions, are very effective in directing the water towards the flame/combustion zone but also due to the improved atomization associated with fuel-water emulsions and mixing that occurs prior to combustion effective in placing the water directly in the combustion region of the engine to obtain optimum results. As well, smoke is often reduced and fuel consumption not adversely effected, for lower W/F ratios (up to 30%). However the variability and level of control over the addition of water to this type of system is a major concern. An excess of water injected into the cylinder either too early or too late in the combustion process can cause cooling of the entire cylinder which may lead to increased ignition delay, engine noise and retarded (or incomplete) combustion, especially for operation at low loads and at stops and starts.

8. TEST DATA ON WATER INJECTION SYSTEMS

The literature survey found experimental data on NOx emissions using Water Injection Systems (WIS) from laboratory tests (dynamometer) and vessel field trials. Table 8.1 below summarizes these tests and trials and Figure 8.1 shows the various WIS configurations employed. For more details on each dataset, readers are directed to the references identified by number in Table 8.1 (Ref.) and listed in the References section.

Table 8.1: WIS Dataset Summary

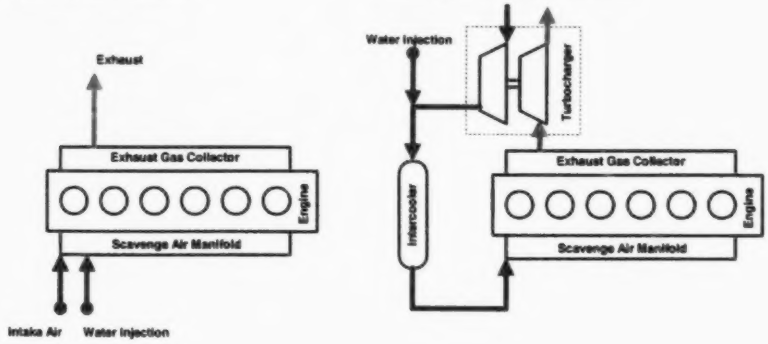
Vessel	Engine	MCR [bhp@rpm]	Cylinder [L]	Test Year	WIS Config.	Ref.
ERMD #1	Cat 3406E (6cyl)	336kW @ 1800rpm	2.43	1998	[B] & [C]	[23]
ERMD #2	Cummins (6cyl)	261kW @ 2100rpm	2.33	1999	[B]	[23]
M/V *OSKI*	Detroit Diesel (12cyl)	268kW @ 1800rpm	1.16	2002	[A]	[36]
M/V *WaveRider*	Detroit Diesel (12cyl)	805kW @ 2300rpm	1.51	2003	[B mod.]	[37]
M/F *Q.N.W.*	Wärtsilä (9cyl)	3375kW @ 750rpm	28.15	1999	[B]	[24]
M/V *Cabot* 2004	Pielstick (12cyl)	5370kW @ 500rpm	57.81	2004	[C]	[21]
M/V *Cabot* 2005	as above	as above	as above	2005	[D]	[55]

Notes:
1) WIS Configuration = ID of WIS configuration sketch in Figure 8.1
2) Reference = see this report reference number for more details

Figure 8.1: WIS Arrangements

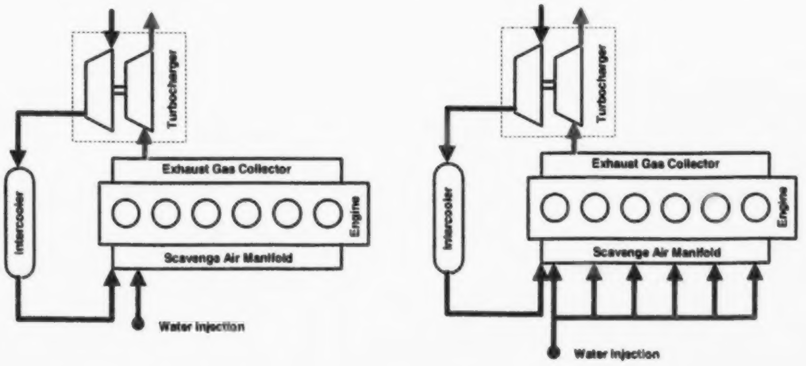
[A]
Naturally Aspirated
Water Injection @ Manifold Head

[B]
Turbocharged
Water Injection BEFORE Intercooler


Exhaust
Exhaust Gas Collector
Engine
Scavenge Air Manifold
Intake Air
Water Injection
Water Injection
Turbocharger
Intercooler
Exhaust Gas Collector
Engine
Scavenge Air Manifold

[C]
Turbocharged
Water Injection AFTER Intercooler
Water Injection @ Manifold Head

[D]
Turbocharged
Water Injection AFTER Intercooler
Water Injection @ Manifold (Each Cylinder)


Turbocharger
Intercooler
Exhaust Gas Collector
Engine
Scavenge Air Manifold
Water Injection
Turbocharger
Intercooler
Exhaust Gas Collector
Engine
Scavenge Air Manifold
Water Injection

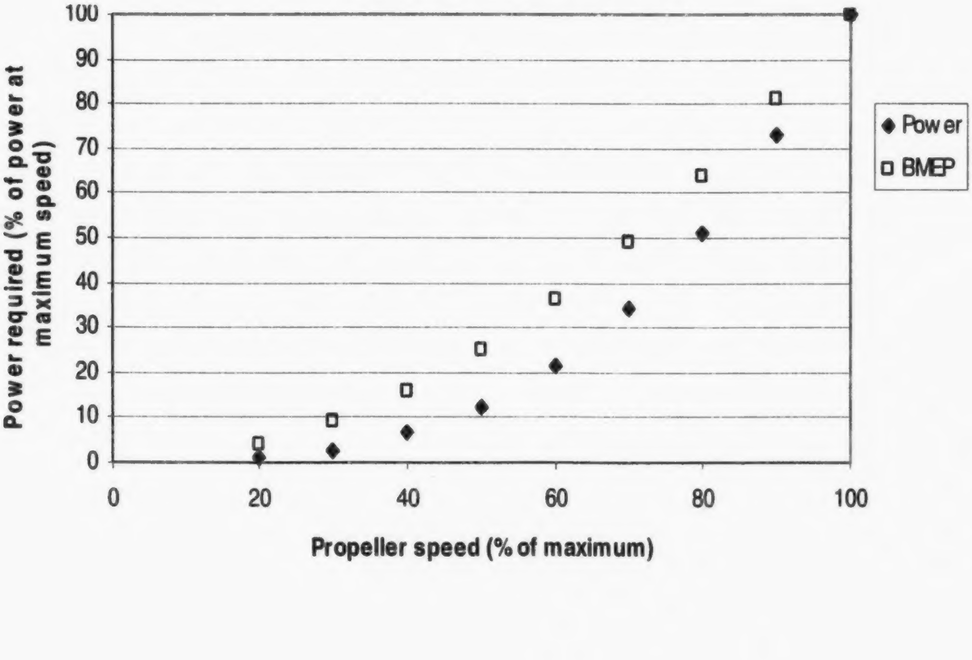
It is recognized that there are drawbacks with the datasets identified in Table 8.1 both individually and collectively, for example:

- Difficulty to define trends due to a limited number of data points.
- Significant scatter observed in data points recorded.
- Different levels of confidence amongst datasets in the results obtained (i.e. some datasets include multiple points averaged to give a result for a specific condition while others are one-shot data; some datasets show baseline data taken before and after testing a specific condition while others do not).
- Different test methodologies between datasets (i.e. specific load testing, cycle testing).
- Different test parameters logged between datasets.

These drawbacks make it difficult to draw firm conclusions or make definite comparisons between datasets. Nevertheless, the datasets are summarized in the following sub-sections for the purposes of (i) summarizing WIS tests/trials completed and data reported and (ii) drawing general conclusions (albeit with the caveat of the problems/concerns noted above) from the results reported.

The first two datasets presented are for heavy-duty truck engines. It should be noted that the marine application is somewhat unique in that, except under transient conditions, engine load and speed are not independent. This situation arises because of propeller characteristics, the power required to drive a propeller rises with the cube of propeller speed. As a result, engine load (torque or BMEP) varies with the square of propeller speed. A truck engine typically has maximum torque at a speed around 50-60% of rated speed and may operate at that condition for long periods of time (i.e. a truck climbing a grade). At 50-60% rated speed, a marine engine at steady conditions is loaded at only about 25-35% of the BMEP achieved at rated power as illustrated in Figure 8.2.

Figure 8.2: Engine Loading



8.1 ERMD Test #1 (Caterpillar 3406 Laboratory Tests)

Laboratory testing was conducted in January 1998 on a Caterpillar 3406E heavy-duty truck engine fitted with a prototype Continuous Water Injection (CWI) system from MA Turbo/Engine Design [40]. The engine used was a stock Caterpillar 3406E (Serial # 5EK66959), 6 cylinder inline (14.6 Litre), 4 cycle, turbocharged, air-to-air cooled engine manufactured in November 1995 [67]. This engine is rated at 336 kW (450 bhp) at 1800 rpm. The engine had new fuel and oil filters and fresh lubricants. Fuel used during testing was #2 Low Sulphur Diesel (LSD).

Two series of tests were completed, one with water injection before (Figure 8.1 [B]) and with water injection after the intercooler (Figure 8.1 [C]). For each test series, various water injection flow rates at three operating modes were tested (L/min) and the weighted emission values calculated:

- Mode 3 (70% load - Transition to Cruise) ~ 311 bhp engine power (311/450 = 0.69)
- Mode 4 (90%load - Open Water Cruise) ~ 400 bhp engine power (400/450 = 0.89)
- Mode 5 (50% load - Dockside Approach) ~ 194 bhp engine power (194/450 = 0.43)
- Weighted = [0.15 x Mode 3] + [0.50 x Mode 4] + [0.35 x Mode 5] = 315 bhp (315/450 = 0.70)

Table 8.1.1 summarizes cycle weighted emissions results; the cycle weighted NOx reduction reported is plotted against the W/F ratio derived from the associated water injection and fuel flow rates as shown in Figure 8.1.1.

Table 8.1.1: Cat 3406E Weighted Emission Results

Bold numbers are averages

Fuel density = 870 kg/m3

[redacted]										
BHP	Water L/min	CO2 [g/bhp-hr]	CO [g/bhp-hr]	NOx [g/bhp-hr]	PM [g/bhp-hr]	BSFC [g/bhp-hr]	% MCR	NOx [g/kWh]	Fuel Rate [L/min]	W/F
Baseline-1										
314.70	0.000	456.36	0.22	1.06	0.033	141.2	69.9%	1.421	0.851	0.000
314.70	0.000	455.41	0.19	1.03	0.025	141.1	69.9%	1.381	0.851	0.000
314.7	**0.000**	**455.89**	**0.21**	**1.05**	**0.029**	**141.2**	**69.9%**	**1.401**	**0.851**	
Series-1	**BEFORE INTERCOOLER**									
315.10	0.256	451.1	0.18	0.81	0.032	140.5	70.0%	1.086	0.848	0.302
314.30	0.358	455.46	0.23	0.76	0.031	140.7	69.8%	1.019	0.847	0.423
314.20	0.376	461.69	0.20	0.73	0.030	140.7	69.8%	0.979	0.847	0.444
314.50	0.385	455.84	0.19	0.70	0.032	140.8	69.9%	0.939	0.848	0.454
314.5		**Series-1 data as % change in Baseline-1 data**					**69.9%**			
	Water L/min	**% CO2 Increase**	**% CO Increase**	**% NOx Reduction**	**% PM Increase**	**% BSFC Increase**				
	0.256	-1.0%	-12.2%	22.5%	10.3%	-0.5%				
	0.358	-0.1%	12.2%	27.3%	6.9%	-0.3%				
	0.376	1.3%	-2.4%	30.1%	3.4%	-0.3%				
	0.385	-0.01%	-7.3%	33.0%	10.3%	-0.2%				
[redacted]										
314.60	0.000	453.99	0.40	0.93	0.033	140.8	69.9%	1.247	0.849	0.000
314.40	0.000	458.04	0.32	1.03	0.021	142.2	69.9%	1.381	0.856	0.000
314.5	**0.000**	**456.0**	**0.36**	**0.98**	**0.027**	**141.5**	**69.9%**	**1.314**	**0.853**	
[redacted]										
314.90	0.333	455.89	0.35	0.74	0.034	142.3	70.0%	0.992	0.858	0.388
314.20	0.358	469.27	0.38	0.85	0.036	148.3	69.8%	1.140	0.893	0.401
313.90	0.403	465.81	0.42	0.73	0.041	142.8	69.8%	0.979	0.859	0.469
314.30	0.435	469.12	0.43	0.74	0.042	143.0	69.8%	0.992	0.861	0.505
314.3		[redacted]					**69.9%**			
	Water L/min	**% CO2 Increase**	**% CO Increase**	**% NOx Reduction**	**% PM Increase**	**% BSFC Increase**				
	0.333	0.0%	-2.8%	[redacted]	25.9%	0.5%				
	0.358	2.9%	5.6%	[redacted]	33.3%	4.8%				
	0.403	2.1%	16.7%	[redacted]	51.9%	0.9%				
	0.435	2.9%	19.4%	[redacted]	55.6%	1.1%				

8.1 ERMIT Test #1 (Caterpillar 3406 Laboratory Tests)

Laboratory testing was conducted in January 1998 on a Caterpillar 3406E heavy duty truck engine fitted with a prototype Continuous Water Injection (CWI) system from MS Tran Engine Design [40]. The engine used was a stock Caterpillar 3406E (Serial # 5EK66959), 6 cylinder inline (14.6 Litre), 4 cycle, turbocharged, air-to-air cooled engine manufactured in November 1995 [67]. This engine is rated at 336 kW (450 bhp) at 1800 rpm. The engine had new fuel and oil filters and fresh lubricants. Fuel used during testing was #2 Low Sulphur Diesel (LSD).

Two series of tests were completed, one with water injection before (Figure 8.1 [B]) and with water injection after the intercooler (Figure 8.1 [C]). For each test series, various water injection flow rates at three operating modes were tested (L/min) and the weighted emission values calculated.

- Mode 3 (70% load - Transition to Cruise) ~ 311 bhp engine power (311/450 = 0.69)
- Mode 4 (90%load - Open Water Cruise) ~ 400 bhp engine power (400/450 = 0.89)
- Mode 5 (50% load - Dockside Approach) ~ 194 bhp engine power (194/450 = 0.43)
- Weighted = [0.15 x Mode 3] + [0.50 x Mode 4] + [0.35 x Mode 5] = 315 bhp (315/450 = 0.70)

Table 8.1.1 summarizes cycle weighted emissions results; the cycle weighted NOx reduction reported is plotted against the W/F ratio derived from the associated water injection and fuel flow rates as shown in Figure 8.1.1.

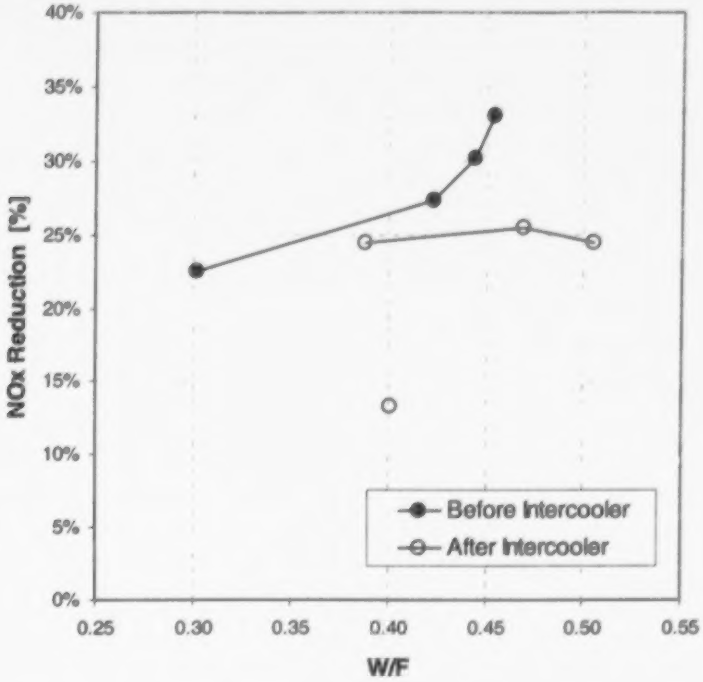
Table 8.1.1: Cat 3406E Weighted Emission Results

Bold numbers are averages

Fuel density = 870 kg/m3

WEIGHTED EMISSIONS [A-7]										
BHP	Water L/min	CO2 [g/bhp-hr]	CO [g/bhp-hr]	NOx [g/bhp-hr]	PM [g/bhp-hr]	BSFC [g/bhp-hr]	% MCR	NOx [g/kWh]	Fuel Rate [L/min]	W/F
Baseline-1										
314.70	0.000	456.38	0.22	1.06	0.033	141.2	69.9%	1.421	0.851	0.000
314.70	0.000	455.41	0.19	1.03	0.025	141.1	69.9%	1.381	0.851	0.000
314.7	**0.000**	**455.89**	**0.21**	**1.05**	**0.029**	**141.2**	**69.9%**	**1.401**	**0.851**	
Series-1	BEFORE INTERCOOLER									
315.10	0.256	451.1	0.18	0.81	0.032	140.5	70.0%	1.086	0.848	0.302
314.30	0.358	455.46	0.23	0.76	0.031	140.7	69.8%	1.019	0.847	0.423
314.20	0.376	461.69	0.20	0.73	0.030	140.7	69.8%	0.979	0.847	0.444
314.50	0.385	455.84	0.19	0.70	0.032	140.8	69.9%	0.939	0.848	0.454
314.5		Series-1 data as % change in Baseline-1 data					69.9%			
	Water L/min	% CO2 Increase	% CO Increase	% NOx Reduction	% PM Increase	% BSFC Increase				
	0.256	-1.0%	-12.2%	22.5%	10.3%	-0.5%				
	0.358	-0.1%	12.2%	27.3%	6.9%	-0.3%				
	0.376	1.3%	-2.4%	30.1%	3.4%	-0.3%				
	0.385	-0.01%	-7.3%	33.0%	10.3%	-0.2%				
Baseline-2										
314.60	0.000	453.99	0.40	0.93	0.033	140.8	69.9%	1.247	0.849	0.000
314.40	0.000	458.01	0.32	1.03	0.021	142.2	69.9%	1.381	0.856	0.000
314.5	**0.000**	**456.0**	**0.36**	**0.98**	**0.027**	**141.5**	**69.9%**	**1.314**	**0.853**	
Series-2	AFTER INTERCOOLER									
314.90	0.333	455.89	0.35	0.74	0.024	142.3	70.0%	0.992	0.856	0.389
314.20	0.358	469.27	0.38	0.85	0.036	148.3	69.8%	1.140	0.893	0.401
313.90	0.403	465.81	0.42	0.73	0.011	142.8	69.8%	0.979	0.858	0.469
314.30	0.435	469.12	0.43	0.74	0.012	143.0	69.8%	0.992	0.851	0.508
314.3		Series-2 data as % change in Baseline-2 data					69.9%			
	Water L/min	% CO2 Increase	% CO Increase	% NOx Reduction	% PM Increase	% BSFC Increase				
	0.333	0.0%	-2.8%	24.5%	25.9%	0.5%				
	0.358	2.9%	5.6%	13.3%	33.3%	1.8%				
	0.403	2.1%	16.7%	25.5%	51.9%	0.8%				
	0.435	2.9%	19.4%	24.5%	55.6%	1.1%				

Figure 8.1.1: Cat 3406E NOx Reduction Weighted Results



Pertinent notes and conclusions from this dataset are:

- Figure 8.1.1 and Table 8.1.1 give cycle-weighted results.
- Baseline (no water injection) NOx emissions for this engine ~ 1.35 g/kWh; while this low NOx emission rate is common for on road vehicles, it is uncommon for marine engine of the same vintage.
- NOx reduction in the range between ~13.3% and 33% was achieved.
- NOx reduction was greater when water was injected before the intercooler.
- The percentage NOx reduction increases with W/F ratio for injection before the intercooler.
- Irrespective of the relationship between NOx reduction and W/F for injection after the intercooler as it seems likely one of lower W/F points (0.388 or 0.401) is an anomaly.
- Nominal (+/- 3%) change in CO_2 emissions with water injection was obtained.
- Scatter in CO emissions data is evident. At the higher W/F ratios, CO emissions appear to decrease when injecting water before the intercooler and increase when injecting after the intercooler.
- Large percentage increase in PM emissions was noted when injecting water. Between 3.4 and 10.3% increase with W/F ratio of 0.302 to 0.454 and between 25.9 and 55.6% increase in PM with W/F ratios of 0.388 to 0.505 for water injection before and after intercooler respectively.
- Nominal (mostly +/- 1%) change in fuel consumption.
- In Figure 8.1.1 the limited number of data points and scatter make it difficult to fit a curve, in particularly through the data point at 0.40 W/F on the After-Intercooler curve.

8.2 ERMD Test #2 (Cummins NTC-350 Laboratory Tests)

Laboratory testing was conducted in January 1999 on a Cummins NTC-350 heavy-duty truck engine fitted with a prototype Continuous Water Injection (CWI) system from MA Turbo/Engine Design [40]. The engine was a stock Cummins (Serial #11146538, CPL 0450), 6-cylinder inline (14.0 Litre), 4 cycle, turbocharged, water-to-air charge after cooled engine built in January 1984 [68]. This engine is rated at 261 kW (350 bhp) at 2100 rpm. Fuel used during testing was #2 Low Sulphur Diesel (LSD).

Water was injected through two atomizing nozzles located immediately before the aftercooler (Figure 8.1 [B]). A test series was conducted at three operating modes and four water injection rates by varying the nozzle water pressures (55, 65,75 and 85 psig). The weighted emission results were calculated:

- Mode 2 (50% load) ~ 180 bhp engine power (180/350 = 0.51)
- Mode 3 (75% load) ~ 260 bhp engine power (260/350 = 0.74)
- Mode 4 (100% load) ~ 330 bhp engine power (330/350 = 0.94)
- Weighted = [0.25 x Mode 2] + [0.30 x Mode 3] + [0.45 x Mode 4] = 272 bhp (272/350 = 0.78)

Test results were based on specific water injection pressures [psig] as opposed to W/F ratio. Cycle weighted NOx reduction achieved were plotted against calculated W/F ratio as shown in Figure 8.2.1. Table 8.2.1 summarizes cycle weighted emissions results.

Figure 8.2.1: Cummins NTC-350 NOx Reduction Weighted Results

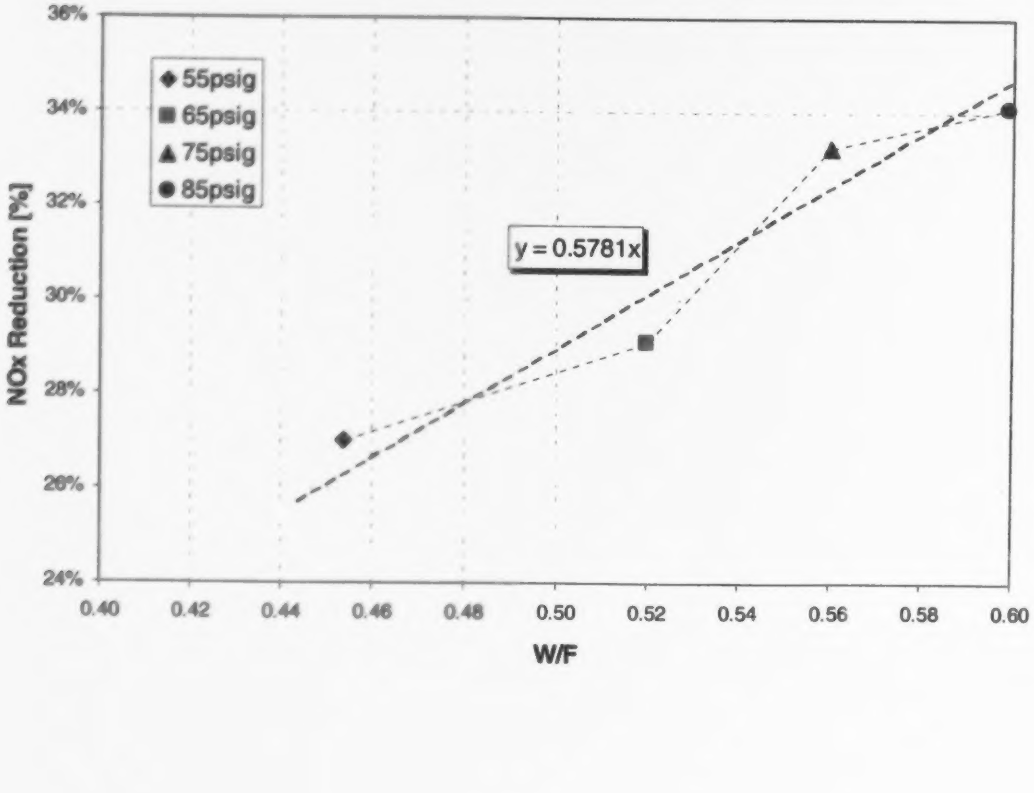


Table 8.2.1: Cummins HTC-350 Weighted Emission Results

Bold numbers are Averages   Fuel Density of 870 g/liter

WEIGHTED EMISSIONS (B-5)										
BHP	Water [L/hr]	CO2 [g/bhp-hr]	CO [g/bhp-hr]	NOx [g/bhp-hr]	THC [g/bhp-hr]	BSFC [g/bhp-hr]	% MCR	NOx [g/kWh]	Fuel Rate [L/hr]	W/F
Baseline-1										
275.10	0.0	532.0	0.82	9.78	0.05	168.2	78.6%	13.088	53.186	0.000
274.80	0.0	533.1	0.81	8.91	0.05	168.5	78.5%	11.919	53.223	0.000
279.50	0.0	528.8	0.81	9.16	0.05	167.2	79.9%	12.281	no data	0.000
Baseline-2										
264.00	0.0	540.5	0.78	8.29	0.05	170.8	75.4%	11.117	51.829	0.000
265.90	0.0	536.6	0.78	8.10	0.05	169.9	76.0%	10.892	51.834	0.000
268.50	0.0	524.2	0.76	8.50	0.05	165.7	76.7%	11.399	51.138	0.000
271.30	**0.0**	**532.5**	**0.79**	**8.79**	**0.05**	**168.3**	**77.5%**	**11.783**	**52.242**	**0.000**
75 psig										
283.70	29.7	507.1	0.95	5.76	0.050	160.4	81.1%	7.724	52.305	0.568
269.70	28.5	537.0	1.01	6.08	0.090	169.9	77.1%	8.153	52.669	0.541
274.40	29.2	512.2	0.94	5.76	0.050	162.0	78.4%	7.724	51.095	0.571
275.9	**29.1**	**518.8**	**0.97**	**5.87**	**0.063**	**164.1**	**78.8%**	**7.867**	**52.0**	**0.560**

	75 psig data as % change in Baseline-1&2 avg. data				
Water L/min	% CO2 Increase	% CO Increase	% NOx Reduction	% THC Increase	% BSFC Increase
29.7	-4.8%	19.7%	34.4%	-3.2%	-4.7%
28.5	0.8%	27.3%	30.8%	74.2%	0.9%
29.2	-3.8%	18.5%	34.4%	-3.2%	-3.8%
29.1	**-2.6%**	**21.8%**	**33.2%**	**22.6%**	**-2.5%**

85 psig										
264.80	31.9	564.2	1.12	6.78	0.060	178.5	75.7%	9.092	54.330	0.587
285.50	32.3	528.3	0.98	6.23	0.060	167.1	81.6%	8.355	54.836	0.589
286.00	31.9	494	0.98	5.35	0.060	156.3	81.7%	7.174	51.381	0.621
278.8	**32.0**	**528.8**	**1.0**	**6.1**	**0.1**	**167.3**	**0.8**	**8.207**	**53.5**	**0.599**

	85 psig data as % change in Baseline-1&2 avg. data				
Water L/min	% CO2 Increase	% CO Increase	% NOx Reduction	% THC Increase	% BSFC Increase
31.9	5.9%	41.2%	22.8%	16.1%	6.0%
32.3	-0.8%	23.5%	29.1%	16.1%	-0.7%
31.9	-7.2%	23.5%	39.1%	16.1%	-7.1%
32.0	**-0.7%**	**29.4%**	**34.1%**	**16.1%**	**-0.6%**

☐ data omitted from average

65 psig										
282.40	25.9	511.3	0.94	6.46	0.060	162.7	80.7%	8.663	52.812	0.490
264.30	26.5	528.7	1.00	6.27	0.050	167.2	75.5%	8.408	50.794	0.522
273.30	28.7	527.8	0.96	5.96	0.050	166.9	78.1%	7.992	52.430	0.547
273.3	**27.0**	**523.6**	**1.0**	**6.2**	**0.1**	**165.6**	**0.8**	**8.355**	**52.0**	**0.520**

	65 psig data as % change in Baseline-1&2 avg. data				
Water L/min	% CO2 Increase	% CO Increase	% NOx Reduction	% THC Increase	% BSFC Increase
	-3.4%	18.5%	26.5%	16.1%	-3.3%
	-0.7%	26.1%	28.6%	-3.2%	-0.7%
	-0.9%	21.0%	32.2%	-3.2%	-0.9%
	-1.7%	**21.8%**	**29.1%**	**3.2%**	**-1.6%**

Baseline-3										
273.30	0.0	538.9	0.86	8.8	0.06	170.4	78.1%	11.801	53.529	0.000
280.30	0.0	518.3	0.82	8.42	0.05	163.8	80.1%	11.291	52.774	0.000
Baseline-4										
276.00	0.0	526.4	0.86	8.66	0.05	166.4	78.9%	11.613	52.789	0.000
272.60	0.0	528.1	0.86	8.28	0.05	166.9	77.9%	11.104	52.295	0.000
275.6	**0.0**	**527.9**	**0.85**	**8.54**	**0.05**	**166.9**	**78.7%**	**11.452**	**52.847**	**0.000**
55 psig										
263.10	23.2	538.6	0.93	5.9	0.050	170.3	75.2%	7.912	51.501	0.450
277.20	25.7	532.1	0.92	6.47	0.050	168.3	79.2%	8.676	53.624	0.479
273.40	23.1	538.1	1.01	6.34	0.050	170.2	78.1%	8.502	53.486	0.432
271.2	**24.0**	**536.3**	**1.0**	**6.2**	**0.1**	**169.6**	**0.8**	**8.364**	**52.9**	**0.451**

	55 psig data as % change in Baseline-3&4 avg. data				
Water L/min	% CO2 Increase	% CO Increase	% NOx Reduction	% THC Increase	% BSFC Increase
	2.0%	9.4%	30.9%	-4.8%	2.1%
	0.8%	8.2%	24.2%	-4.8%	0.9%
	1.9%	18.8%	25.8%	-4.8%	2.0%
	1.6%	**12.2%**	**27.0%**	**-4.8%**	**1.6%**

Table 8.2.1: Cummins NTC-350 Weighted Emission Results

Bold numbers are averages

Fuel density = 870 kg/m3

BHP	Water [L/hr]	CO2 [g/bhp-hr]	CO [g/bhp-hr]	NOx [g/bhp-hr]	THC [g/bhp-hr]	BSFC [g/bhp-hr]	% MCR	NOx [g/kWh]	Fuel Rate [L/hr]	W/F
Baseline-1										
275.10	0.0	532.0	0.82	9.76	0.06	168.2	78.6%	13.088	53.186	0.000
274.80	0.0	533.1	0.81	8.91	0.05	168.5	78.5%	11.949	53.223	0.000
279.50	0.0	528.8	0.81	9.16	0.05	167.2	79.9%	12.284	no data	0.000
Baseline-2										
264.00	0.0	540.5	0.78	8.29	0.05	170.8	75.4%	11.117	51.829	0.000
265.90	0.0	536.6	0.78	8.10	0.05	169.6	76.0%	10.862	51.835	0.000
268.50	0.0	524.2	0.76	8.50	0.05	165.7	76.7%	11.399	51.138	0.000
271.30	**0.0**	**532.5**	**0.79**	**8.79**	**0.05**	**168.3**	**77.5%**	**11.783**	**52.242**	**0.000**
283.70	29.7	507.1	0.95	5.76	0.050	160.4	81.1%	7.724	52.305	0.568
269.70	28.5	537.0	1.01	6.08	0.090	169.9	77.1%	8.153	52.669	0.541
274.40	29.2	512.2	0.94	5.76	0.050	162.0	78.4%	7.724	51.095	0.571
275.9	**29.1**	**518.8**	**0.97**	**5.87**	**0.063**	**164.1**	**78.8%**	**7.867**	**52.0**	**0.560**

Water L/min	% CO2 Increase	% CO Increase	% NOx Reduction	% THC Increase	% BSFC Increase
29.7	-4.8%	19.7%	34.4%	-3.2%	-4.7%
28.5	0.8%	27.3%	30.8%	74.2%	0.9%
29.2	-3.8%	18.5%	34.4%	-3.2%	-3.8%
29.1	**-2.6%**	**21.8%**	**33.2%**	**22.6%**	**-2.5%**

264.80	31.9	564.2	1.12	6.78	0.060	178.5	75.7%	9.092	54.330	0.587
285.50	32.3	528.3	0.98	6.23	0.060	167.1	81.6%	8.355	54.836	0.589
286.00	31.9	494	0.98	5.35	0.060	156.3	81.7%	7.174	51.381	0.621
278.8	**32.0**	**528.8**	**1.0**	**6.1**	**0.1**	**167.3**	**0.8**	**8.207**	**53.5**	**0.599**

Water L/min	% CO2 Increase	% CO Increase	% NOx Reduction	% THC Increase	% BSFC Increase
31.9	5.9%	41.2%	22.8%	16.1%	6.0%
32.3	-0.8%	23.5%	29.1%	16.1%	-0.7%
31.9	-7.2%	23.5%	39.1%	16.1%	-7.1%
32.0	**-0.7%**	**29.4%**	**34.1%**	**16.1%**	**-0.6%**

▨ data omitted from average

282.40	25.9	514.3	0.94	6.46	0.060	162.7	80.7%	8.663	52.812	0.490
264.30	26.5	528.7	1.00	6.27	0.050	167.2	75.5%	8.408	50.794	0.522
273.30	28.7	527.8	0.96	5.96	0.050	166.9	78.1%	7.992	52.430	0.547
273.3	**27.0**	**523.6**	**1.0**	**6.2**	**0.1**	**165.6**	**0.8**	**8.355**	**52.0**	**0.520**

Water L/min	% CO2 Increase	% CO Increase	% NOx Reduction	% THC Increase	% BSFC Increase
	-3.4%	18.5%	26.5%	16.1%	-3.3%
	-0.7%	26.1%	28.6%	-3.2%	-0.7%
	-0.9%	21.0%	32.2%	-3.2%	-0.9%
	-1.7%	**21.8%**	**29.1%**	**3.2%**	**-1.6%**

Baseline-3										
273.30	0.0	538.9	0.86	8.8	0.06	170.4	78.1%	11.801	53.529	0.000
280.30	0.0	518.3	0.82	8.42	0.05	163.8	80.1%	11.291	52.774	0.000
Baseline-4										
276.00	0.0	526.4	0.86	8.66	0.05	166.4	78.9%	11.613	52.789	0.000
272.60	0.0	528.1	0.86	8.28	0.05	166.9	77.9%	11.104	52.295	0.000
275.6	**0.0**	**527.9**	**0.85**	**8.54**	**0.05**	**166.9**	**78.7%**	**11.452**	**52.847**	**0.000**
263.10	23.2	538.6	0.93	5.9	0.050	170.3	75.2%	7.912	51.501	0.450
277.20	25.7	532.1	0.92	6.47	0.050	168.3	79.2%	8.676	53.624	0.479
273.40	23.1	538.1	1.01	6.34	0.050	170.2	78.1%	8.502	53.486	0.432
271.2	**24.0**	**536.3**	**1.0**	**6.2**	**0.1**	**169.6**	**0.8**	**8.364**	**52.9**	**0.454**

Water L/min	% CO2 Increase	% CO Increase	% NOx Reduction	% THC Increase	% BSFC Increase
	2.0%	9.4%	30.9%	-4.8%	2.1%
	0.8%	8.2%	24.2%	-4.8%	0.9%
	1.9%	18.8%	25.8%	-4.8%	2.0%

Pertinent notes and conclusions from this dataset are:

- Figure 8.2.1 and Table 8.2.1 present cycle weighted results.
- Baseline (no water injection) NOx emissions for this engine at ~ 11.65 g/kWh.
- NOx reduction achieved ranges between ~27.0 and 33.2%.
- The percentage NOx reduction increases with W/F ratio. Straight line fit through the data points gives NOx reduction [%] = 57.81 x W/F ratio.
- Nominal CO_2 emissions with water injection varied within +/- 3%.
- Significant increase in CO emissions from 12.2 to 29.4%) with increasing W/F ratio.
- HC emissions were significantly higher at 16.1 and 22.6% at the higher W/F ratios tested (0.599 and 0.560 W/F respectively).
- Nominal fuel consumption change within +/-3%.
- Large range of scatter found in emissions data. For example, for the same condition (3 points reported for each condition) we have: a range of 8.2 to 18.8% CO increase at 55 psig and a range of 22.8 to 39.1% decrease in NOx at 85 psig. This suggests experimental and/or instrumentation errors.

8.3 M/V *OSKI*

The M/V *OSKI* is a 12 kn 396 passenger ferry built in 1979. The Blue & Gold Fleet of San Francisco, California operates the ferry in San Francisco Bay. The 85' x 24' x 7' vessel shown in Figure 8.3.1 is powered by two Detroit Diesel 12V-71NA-7122-700 engines. These 12 cylinder naturally aspirated engines have a displacement of 852 cu.in. (1.16 L/cyl.), and develop 360 bhp at 1800 rpm.

Figure 8.3.1: M/V *OSKI*

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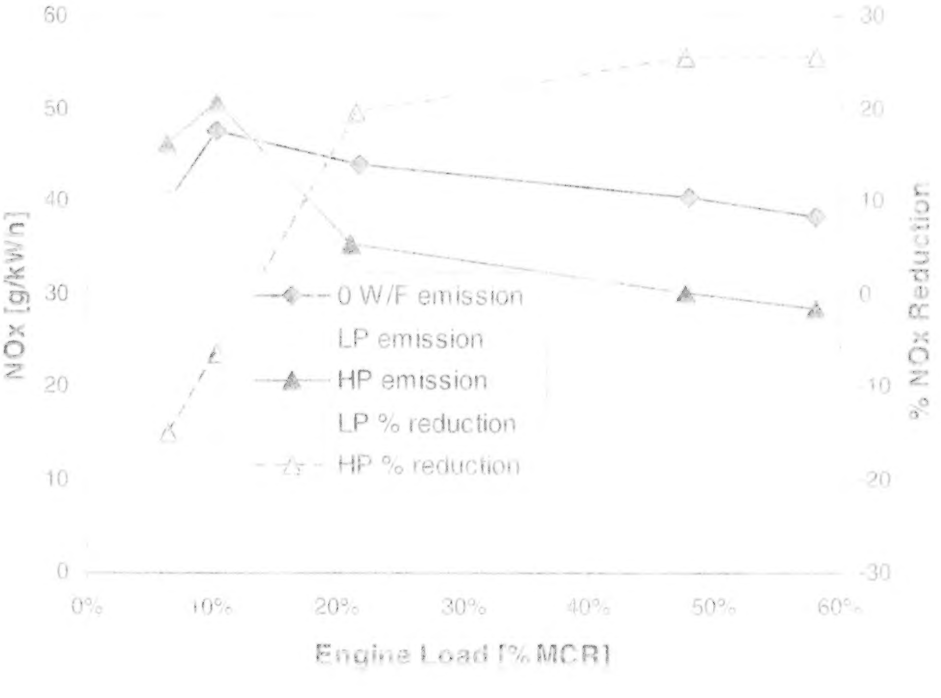
Emission testing was conducted in 2001 [43] on the starboard engine using off-road low sulphur EPA diesel (red). A Continuous Water Injection (CWI) system from MA Turbo/Engine Design was fitted to reduce emissions as illustrated in Figure 8.1 [A]. Water injection testing was conducted at 60 psi (low pressure, LP) and 85 psi (high pressure, HP) injection nozzle pressure. The results are shown in Table 8.3.1 and Figure 8.3.2. No water flow rates were given in the test report so NOx reduction cannot be plotted against W/F ratio. It should also be noted that engines were over the normal rebuild hours and the WIS was not activate below 1200 rpm (shaded cells in Table 8.3.1).

Table 8.3.1: M/V *OSKI* Emission Results

BHP	RPM	CO [g/bhp-hr]	NOx [g/bhp-hr]	SO2 [g/bhp-hr]	% MCR	NOx [g/kWh]
Diesel Baseline						
23.9	641	7.33	29.9	0	6.6%	40.10
37.4	891	0.88	35.5	0	10.4%	47.61
78.6	1208	0	32.7	0	21.8%	43.85
172.5	1565	0	30.1	0	47.9%	40.36
208.9	1660	0	28.5	0	58.0%	38.22
Diesel With Low-Pressure (LP) Water Injection						
23.7	637	7.69	29.7	0	6.6%	39.83
38	939	1.31	39	0	10.6%	52.30
77.3	1201	0.41	24.8	0	21.5%	33.26
170.7	1560	0	23.1	0	47.4%	30.98
208.9	1660	0	22	0	58.0%	29.50
Diesel With High-Pressure (HP) Water Injection						
23.2	623	5.16	34.4	0	6.4%	46.13
37.8	855	1.67	37.8	0	10.5%	50.69
75.9	1193	0.32	26.3	0	21.1%	35.27
171.8	1563	0	22.4	0	47.7%	30.04
208.9	1660	0	21.2	0	58.0%	28.43

% MCR	AVG RPM	Base NOx zero W/F	NOx [g/kWh]		NOx Reduction [%]	
			LP	HP	LP	HP
6.6%	634	40.10	39.83	46.13	0.67	-15.05
10.5%	895	47.61	52.30	50.69	-9.86	-6.45
21.5%	1,201	43.85	33.26	35.27	24.16	19.57
47.7%	1,563	40.36	30.98	30.04	23.26	25.58
58.0%	1,660	38.22	29.50	28.43	22.81	25.61

Figure 8.3.2: M/V *OSKI* Test Results



Pertinent notes and conclusions from this dataset are:

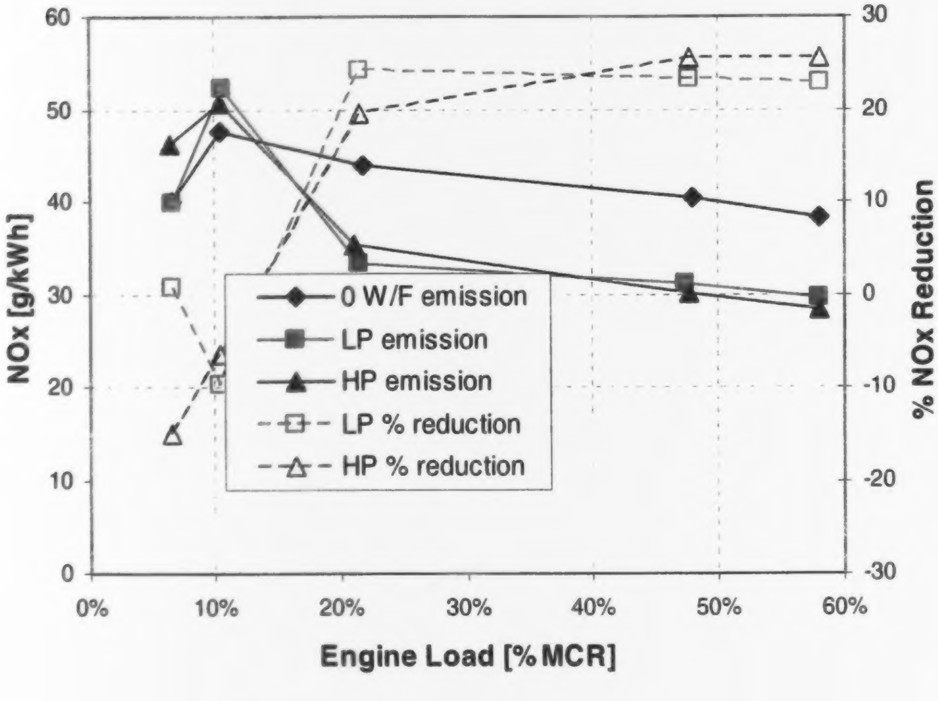
- In Figure 8.3.2, the data points below 20% engine load should be ignored, as the WIS was not activated (less than 1200 rpm). They are plotted simply as record of the data reported and to provide an additional point to the baseline W/F curve (W/F=0).

Table 8.3.1: M/V *OSKI* Emission Results

BHP	RPM	CO [g/bhp-hr]	NOx [g/bhp-hr]	SO2 [g/bhp-hr]	% MCR	NOx [g/kWh]
Diesel Baseline						
23.9	641	7.33	29.9	0	6.6%	40.10
37.4	861	0.88	35.5	0	10.4%	47.61
78.6	1208	0	32.7	0	21.8%	43.85
172.5	1565	0	30.1	0	47.9%	40.36
208.9	1660	0	28.5	0	58.0%	38.22
[redacted]						
23.7	637	7.69	29.7	0	6.6%	39.83
38	889	1.34	39	0	10.6%	52.30
77.3	1201	0.41	24.8	0	21.5%	33.26
170.7	1560	0	23.1	0	47.4%	30.98
208.9	1660	0	22	0	58.0%	29.50
[redacted]						
23.2	623	5.16	34.4	0	6.4%	46.13
37.8	886	1.87	37.8	0	10.5%	50.69
75.9	1193	0.32	26.3	0	21.1%	35.27
171.8	1563	0	22.4	0	47.7%	30.04
208.9	1660	0	21.2	0	58.0%	28.43

% MCR	AVG RPM	Base NOx zero W/F	NOx [g/kWh]		NOx Reduction [%]	
			LP	HP	LP	HP
6.6%	634	40.10	39.83	46.13	0.67	-15.05
10.5%	865	47.61	52.30	50.69	-9.86	-6.48
21.5%	1,201	43.85	33.26	35.27	24.16	19.57
47.7%	1,563	40.36	30.98	30.04	23.26	25.58
58.0%	1,660	38.22	29.50	28.43	22.81	25.61

Figure 8.3.2: M/V *OSKI* Test Results



Pertinent notes and conclusions from this dataset are:

- In Figure 8.3.2, the data points below 20% engine load should be ignored, as the WIS was not activated (less than 1200 rpm). They are plotted simply as record of the data reported and to provide an additional point to the baseline W/F curve (W/F=0).

- NOx emissions (g/kWh) shown decrease with engine load. This is common for marine applications where the engine is operated on a propeller curve where not only engine load but also engine speed changes.
- NOx reduction between ~19.57 and 25.61% was achieved.
- The LP and HP emission data points show convergence towards the zero W/F baseline showing the WIS as inactive (percentage curves should go to zero)
- HP water injection yields ~5% lower NOx reduction than LP injection at ~20% load. Above 40% MCR, HP injection yields higher (~3%). NOx reduction.
- Data not given to enable conversion of LP and HP to W/F ratio.
- NOx emission values around 40 g/kWh are high for an engine of this power.

The high NOx emissions for this engine may be a function of age (1979) and maintenance condition (overdue for rebuild). Detroit Diesel engines have camshaft operated unit injectors, on the older models, there is a single value of injection timing that has to serve over the entire engine load/speed range. Modern engines have electronically controlled unit injectors that optimise injection timing over the entire load/speed range. A possible explanation for the high NOx emission value is that the injection timing was set too far advanced or alternatively had been "optimized" to provide maximum fuel economy for the full power (high speed) condition.

8.4 M/V *WaveRider*

The M/V *WaveRider* is a 149 passenger, water-jet propelled hydrofoil ferry operated by SCX, Inc. in San Diego, California. The 80 ft. vessel shown in Figure 8.4.1 is powered by four Detroit Diesel 12V92 engines (model year 1981). These 12 cylinders turbocharged engines have a displacement of 1104 cu.in. (~1.51 L/cyl.) and develop 1080 bhp at 2300 rpm.

Emission testing was conducted in 2003 [44] on the starboard forward engine. A Continuous Water Injection (CWI) system from MA Turbo/Engine Design injected water injection into the air stream between the turbocharger outlet and supercharger inlet (replace intercooler on Figure 8.1[B] with turbocharger). Testing was conducted at with regular (0.395 %wt) and low sulphur (0.032 %wt) diesel fuel at engine speeds between 1900 and 2100 rpm. The results are shown in Figure 8.4.2 and Table 8.4.1. No water flow rate or fuel consumption data was published in the test report. The report also noted that the low sulphur fuel used might have been contaminated.

Figure 8.4.1: M/V *WaveRider*

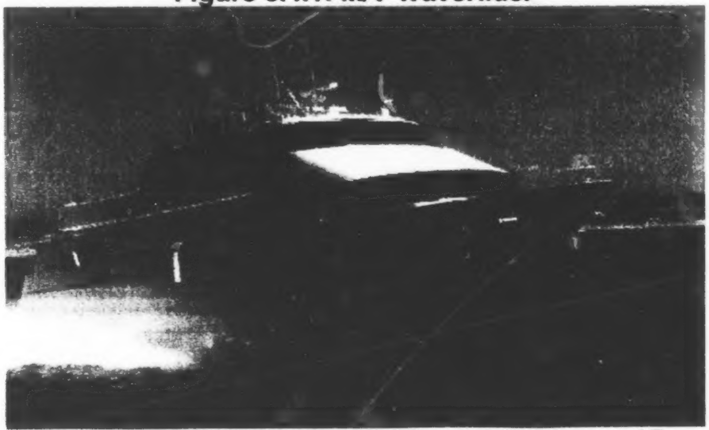


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Figure 8.4.2: M/V *WaveRider* Test Results

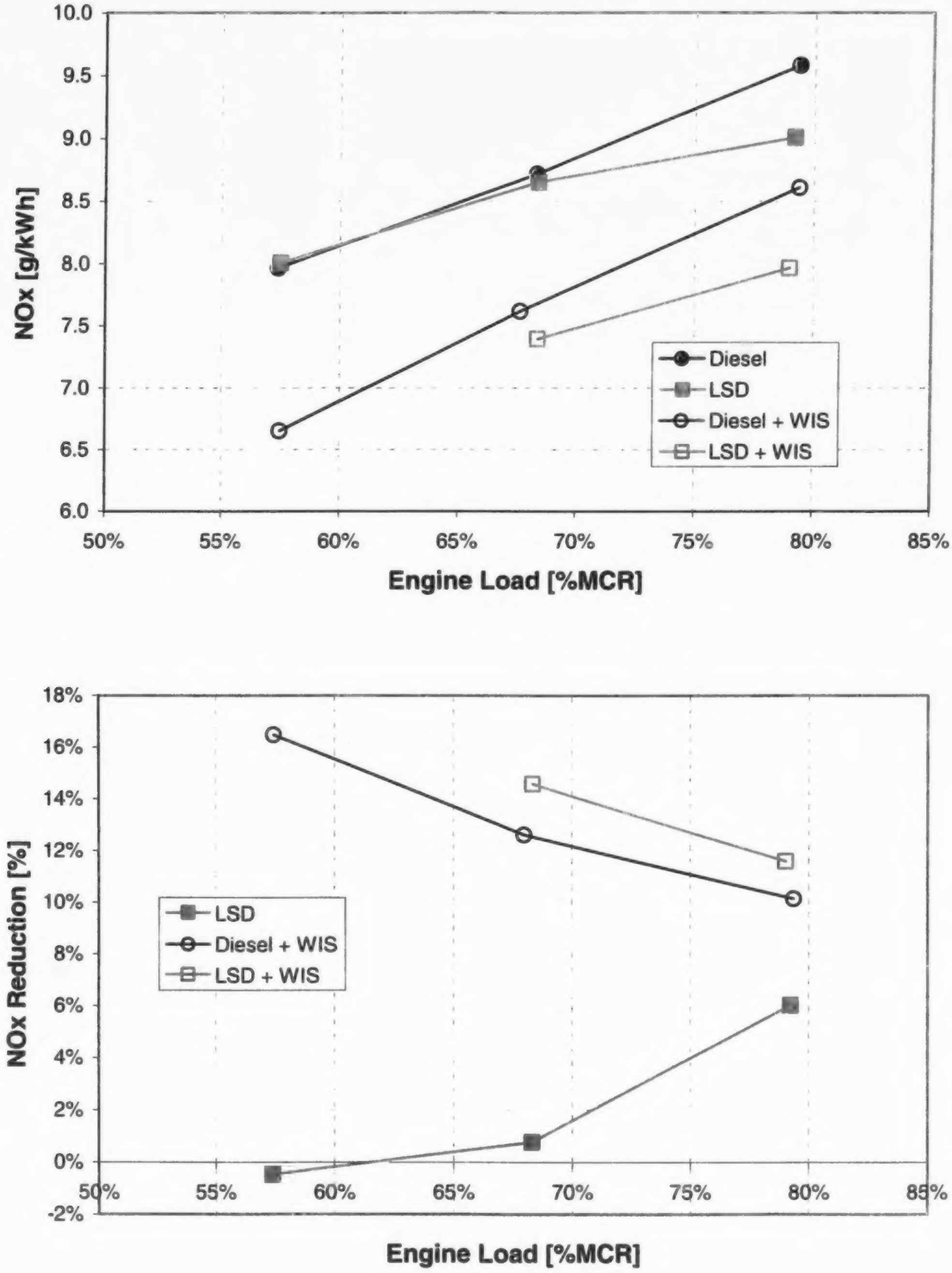


Table 8.4.1: M/V *WaveRider* Emission Test Results

BHP	RPM	BSNOx [g/bhp-hr]	BSFC [lb/bhp-hr]	BSPM [g/bhp-hr]	% MCR	NOx [g/kWh]
Marine Diesel Baseline						
857.0	2100	7.145	0.407	0.17	79.4%	9.582
737.7	2000	6.499	0.402	0.192	68.3%	8.715
620.0	1900	5.939	0.405	0.26	57.4%	7.964
[redacted]						
857.1	2100	6.42	0.409	0.171	79.4%	8.609
730.4	2000	5.679	0.402	0.179	67.6%	7.616
620.8	1900	4.96	0.405	0.246	57.5%	6.651
857.1			-0.5%	-0.6%	79.4%	10.1%
734.1			0.0%	6.8%	68.0%	12.6%
620.4			0.0%	5.4%	57.4%	16.5%
Low Sulphur Diesel						
854.4	2100	6.717	0.403	0.099	79.1%	9.008
737.7	2000	6.451	0.397	0.112	68.3%	8.651
620.4	1900	5.969	0.399	0.16	57.4%	8.005
[redacted]						
852.2	2100	5.94	0.404	0.096	78.9%	7.966
737.7	2000	5.512	0.401	0.105	68.3%	7.392
no data	1900	no data	no data	no data	no data	no data
852.2			-0.2%	3.0%	79.0%	11.6%
737.7			-1.0%	6.3%	68.3%	14.6%
LSD to Baseline Compare						
855.7			1.0%	41.8%	79.2%	6.0%
737.7			1.2%	41.7%	68.3%	0.7%
620.2			1.5%	38.5%	57.4%	-0.5%

Pertinent notes and conclusions from this dataset are:

- These are not cycle-weighted results.
- For regular diesel operation, water injection resulted in between ~10.1 and 16.5% NOx reduction. Between 11.6 and 14.6% reduction was achieved for LSD operation (missing data at 1900 rpm).
- A ~2% higher NOx reduction achieved with WIS and with the engine operating at ~70-80% MCR and using LSD instead of regular diesel. The LSD used may have been contaminated.
- Without the WIS active, ~2% higher at 70% MCR and ~6% higher at 80% MCR when burning LSD instead of regular diesel.
- NOx reduction percentage declines with increased engine load with the CWI water injection system in operation. This is due to decreased W/F ratio as load increases (Water constant and Fuel increasing thus W/F decreasing with load). In addition, as load increases the charge air pressure increases (reduced differential nozzle pressure reduces water injected into the system).
- There are some unknowns in this dataset, most notably the quantity of water being injected by the WIS and details on data smoothing undertaken to arrive at the data values reported.

8.5 M/F *Q.N.W.*

The M/F *Queen of New Westminster* is a 87,856 GRT Ro-Ro passenger ferry operated by B.C. Ferries between Vancouver and Nanaimo (Tsawwassen-Duke Point), British Columbia. The 426 ft. length vessel shown in Figure 8.5.1 was launched in 1964 and later re-engined. The current arrangement consists of four Wärtsilä 9-cylinder in-line (28.1 L/cyl) 9R32D turbocharged diesel engines developing 3375 kW (4526 hp) at 750 rpm.

Emission testing was conducted in 1999/2000 [41] on the #4 main engine. A Continuous Water Injection (CWI) system from MA Turbo was fitted, Figure 8.1[B]. Testing was conducted at four

Table 8.4.1: M/V *WaveRider* Emission Test Results

BHP	RPM	BSNOx (g/bhp-hr)	BSFC (lb/bhp-hr)	BSPM (g/bhp-hr)	% MCR	NOx (g/kWh)
Marine Diesel Baseline						
857.0	2100	7.145	0.407	0.17	79.4%	9.583
737.7	2000	6.499	0.402	0.192	68.3%	5.715
620.0	1900	5.939	0.405	0.28	57.4%	7.964
Marine Diesel + WIS						
857.1	2100	6.42	0.409	0.171	79.4%	8.809
730.4	2000	5.679	0.402	0.179	67.6%	7.818
620.8	1900	4.96	0.405	0.246	57.5%	6.651
857.1			-0.5%	-0.6%	79.4%	10.1%
731.1			0.0%	6.8%	68.0%	12.6%
620.4			0.0%	5.4%	57.4%	16.5%

Low Sulphur Diesel						
854.4	2100	6.717	0.403	0.099	79.1%	9.008
737.7	2000	6.451	0.397	0.112	68.3%	8.651
620.4	1900	5.969	0.399	0.16	57.4%	8.005
Low Sulphur Diesel + WIS						
852.2	2100	5.94	0.404	0.098	78.9%	7.966
737.7	2000	5.512	0.401	0.105	68.3%	7.392
no data	1900	no data	no data	no data	no data	no data
852.2			-0.2%	3.0%	79.0%	11.6%
737.7			-1.0%	6.3%	68.3%	14.6%

LSD to Baseline Compare						
855.7			1.0%	41.8%	79.2%	6.0%
737.7			1.2%	41.7%	68.3%	0.7%
620.2			1.5%	38.5%	57.4%	-0.5%

Pertinent notes and conclusions from this dataset are:

- These are not cycle-weighted results.
- For regular diesel operation, water injection resulted in between ~10.1 and 16.5% NOx reduction. Between 11.6 and 14.6% reduction was achieved for LSD operation (missing data at 1900 rpm).
- A ~2% higher NOx reduction achieved with WIS and with the engine operating at ~70-80% MCR and using LSD instead of regular diesel. The LSD used may have been contaminated.
- Without the WIS active, ~2% higher at 70% MCR and ~6% higher at 80% MCR when burning LSD instead of regular diesel.
- NOx reduction percentage declines with increased engine load with the CWI water injection system in operation. This is due to decreased W/F ratio as load increases (Water constant and Fuel increasing thus W/F decreasing with load). In addition, as load increases the charge air pressure increases (reduced differential nozzle pressure reduces water injected into the system).
- There are some unknowns in this dataset, most notably the quantity of water being injected by the WIS and details on data smoothing undertaken to arrive at the data values reported.

8.5 *M/F Q.N.W.*

The M/F *Queen of New Westminster* is a 87,856 GRT Ro-Ro passenger ferry operated by B.C. Ferries between Vancouver and Nanaimo (Tsawwassen-Duke Point), British Columbia. The 426 ft length vessel shown in Figure 8.5.1 was launched in 1964 and later re-engined. The current arrangement consists of four Wärtsilä 9-cylinder in-line (28.1 L/cyl) 9R32D turbocharged diesel engines developing 3375 kW (4526 hp) at 750 rpm.

Emission testing was conducted in 1999/2000 [41] on the #4 main engine. A Continuous Water Injection (CWI) system from MA Turbo was fitted, Figure 8.1[8]. Testing was conducted at four different W/F ratios (achieved through combination of different nozzles and injection [illegible]) at 75% MCR (272 rpm) using No.2 diesel. Table 8.5.1 and Figure 8.5.2 present the test data.

Figure 8.5.1: M/F *Queen of New Westminster*

Table 8.5.1: M/F *Queen of New Westminster* Emission Test Results

Bold numbers are averages. Fuel Density = 870 [kg/m3]

Test	BHP [hp]	RPM	Fuel Rate (L/min)	Water Flow (L/min)	W/F	CO [kg/mtf]	CO2 [kg/mtf]	NOx [kg/mtf]	% MCR	BHP [kW]	Fuel [mt/hr]	NOx [g/kWh]
Diesel Baseline												
1-baseline	3325	272	8.42	0	-	2.18	3124	75.5	73.5%	2479.5	0.440	13.384
2-baseline	3326	272	8.39	0	-	2.18	3127	74.5	73.5%	2480.2	0.438	13.155
3-baseline	3322	272	8.36	0	-	2.12	3128	74.4	73.4%	2477.2	0.436	13.106
4-baseline	3320	272	8.40	0	-	2.18	3127	74.7	73.4%	2475.7	0.438	13.230
5-baseline	3320	272	8.37	0	-	2.18	3127	74.8	73.4%	2475.7	0.437	13.201
6-baseline	3322	272	8.36	0	-	2.25	3128	75.4	73.4%	2477.2	0.436	13.283
AVERAGE	**3,323**	**272**	**8.383**	**0.000**		**2.18**	**3,126.83**	**74.9**	**73.4%**	**2477.6**	**0.438**	**13.226**
Diesel with WIS												
1-WIS	3350	272	8.38	1.3	0.155	2.15	3127	67.4	74.0%	2498.1	0.437	11.802
2-WIS	3360	272	8.39	1.5	0.179	2.18	3127	67	74.2%	2505.6	0.438	11.711
3-WIS	3360	272	8.39	2.1	0.250	2.12	3127	63.3	74.2%	2505.6	0.436	11.065
4-WIS	3365	272	8.40	3.3	0.393	2.21	3127	58.3	74.3%	2509.3	0.433	10.189

		% Change Relative to Baseline			
1-WIS	0.155	-1.45%	0.01%	-9.99%	74.0%
2-WIS	0.179	-0.08%	0.01%	-10.53%	74.2%
3-WIS	0.250	-2.63%	0.01%	-15.47%	74.2%
4-WIS	0.393	1.30%	0.01%	-22.15%	74.3%

Pertinent notes and conclusions from this dataset are:

- NOx reduction of between -9.99 and 22.15% achieved with the water injection system.
- A near linear relationship exists between NOx reduction and W/F ratio in the range of 15 and 40%.
- Nominal change (within +/-3%) in CO emissions with water injection.
- Essentially zero change in CO_2 emissions reported with water injection.
- A 0.08% increase in fuel rate with water injection appears to give 1.09% increase in power.
- These are not cycle-weighted results.
- Low W/F ratios (0.155 - 0.393) were tested.

different W/F ratios (achieved through combination of different nozzles and injection pressures) at ~74% MCR (272 rpm) using No.2 diesel. Table 8.5.1 and Figure 8.5.2 present the test data.

Figure 8.5.1: M/F *Queen of New Westminster*

BCFerries
Queen of New Westminster

Table 8.5.1: M/F *Queen of New Westminster* Emission Test Results

Bold numbers are averages

Fuel Density = 870 [kg/m3]

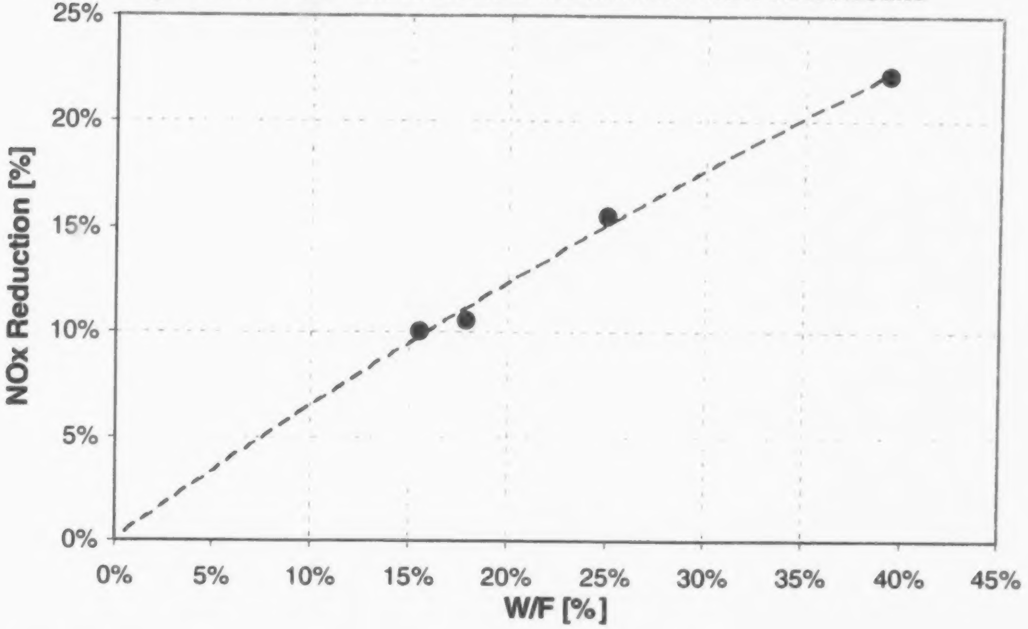
Test	BHP [hp]	RPM	Fuel Rate [L/min]	Water Flow [L/min]	W/F	CO [kg/mtf]	CO2 [kg/mtf]	NOx [kg/mtf]	% MCR	BHP [kW]	Fuel [mt/hr]	NOx [g/kWh]
Diesel Baseline												
1 -baseline	3325	272	8.42	0	-	2.18	3124	75.5	73.5%	2479.5	0.440	13.384
2-baseline	3326	272	8.39	0	-	2.18	3127	74.5	73.5%	2480.2	0.438	13.155
3-baseline	3322	272	8.36	0	-	2.12	3128	74.4	73.4%	2477.2	0.436	13.106
4-baseline	3320	272	8.40	0	-	2.18	3127	74.7	73.4%	2475.7	0.438	13.230
5-baseline	3320	272	8.37	0	-	2.18	3127	74.8	73.4%	2475.7	0.437	13.201
6-baseline	3322	272	8.36	0	-	2.25	3128	75.4	73.4%	2477.2	0.436	13.283
AVERAGE	**3,323**	**272**	**8.383**	**0.000**	-	**2.18**	**3,126.83**	**74.9**	**73.4%**	**2477.6**	**0.438**	**13.226**
1-WIS	3350	272	8.38	1.3	0.155	2.15	3127	67.4	74.0%	2498.1	0.437	11.802
2-WIS	3360	272	8.39	1.5	0.179	2.18	3127	67	74.2%	2505.6	0.438	11.711
3-WIS	3360	272	8.39	2.1	0.250	2.12	3127	63.3	74.2%	2505.6	0.438	11.065
4-WIS	3365	272	8.40	3.3	0.393	2.21	3127	58.3	74.3%	2509.3	0.438	10.188

		% Change Relative to Baseline			
1-WIS	0.155	-1.45%	0.01%	-9.99%	74.0%
2-WIS	0.179	-0.08%	0.01%	-10.53%	74.2%
3-WIS	0.250	-2.83%	0.01%	-15.47%	74.2%
4-WIS	0.393	1.30%	0.01%	-22.15%	74.3%

Pertinent notes and conclusions from this dataset are:

- NOx reduction of between ~9.99 and 22.15% achieved with the water injection system.
- A near linear relationship exists between NOx reduction and W/F ratio in the range of 15 and 40%.
- Nominal change (within +/-3%) in CO emissions with water injection.
- Essentially zero change in CO_2 emissions reported with water injection.
- A 0.08% increase in fuel rate with water injection appears to give 1.09% increase in power.
- These are not cycle-weighted results.
- Low W/F ratios (0.155 - 0.393) were tested.

Figure 8.5.2: M/F *Queen of New Westminster* NOx Test Results



8.6 M/V *Cabot* 2004

The M/V Cabot is a 14,596 GRT, 644 TEU Ro-Ro containership operated by Oceanex between Montreal and St. John's. The vessel (185.27 m length x 22.52 m beam) shown in Figure 8.6.1 was built in 1979 and is powered by twin Pielstick PC 2.5 V-12 engines (57.81 Litre/cylinder displacement), each rated at 5365.5 kW at 500 rpm.

Figure 8.6.1: M/V *Cabot*

Emissions testing was conducted in March 2004 [28] using a Water Injection System (WIS) designed and developed by TDC. Water is injected into the charge air manifold after the intercooler through three pairs of nozzles in each bank of the V-12 engine; Figure 8.1 [C]. Testing was conducted with MDO (0.394% wt sulphur) and IFO (1.3% wt sulphur) at various rpm and water flow rates. Table 8.6.1 and Figure 8.6.2 summarizes the test results.

Figure 8.6.1: M/V *Cabot* 2004 Emission Test Results

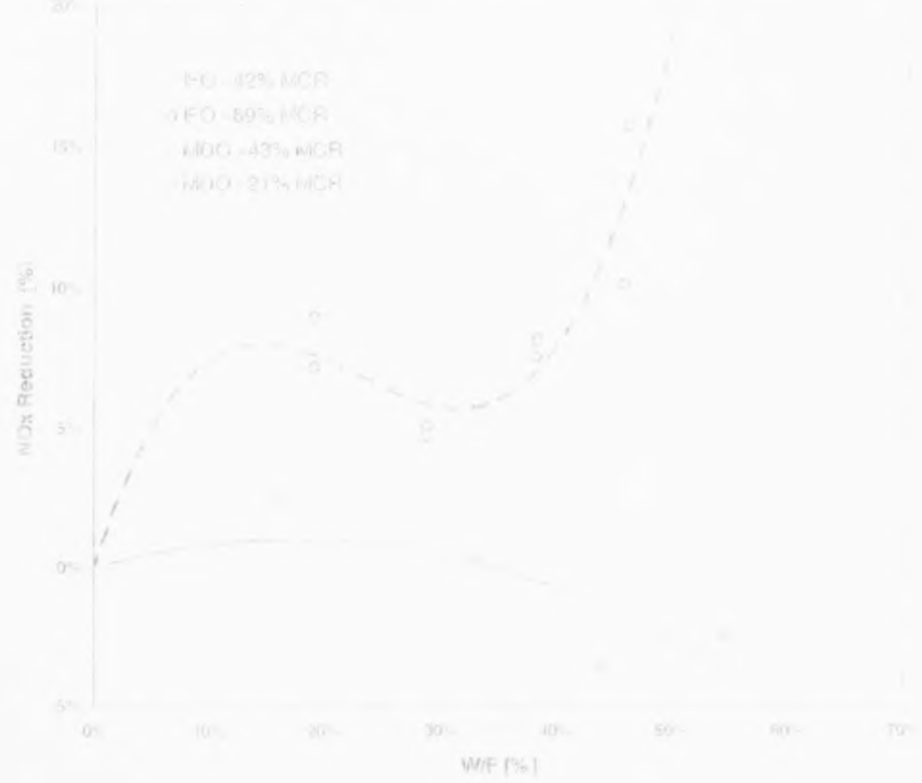


Table 8.6.1: M/V *Cabot* 2004 Emission Test Results

Actual Load % MCR	Actual % Water	Nox Reduction %	CO2 Increase %	CO Increase %	PM Increase %	NOx [g/kWh]	Effect
IFO							
42.7%	0.0%					24.882	
41.99%	28.8%	-0.7%	6.2%	6.4%	20.4%	25.046	(0.023)
41.72%	41.9%	1.7%	6.8%	16.1%	25.5%	24.469	0.040
42.53%	51.2%	-1.3%	5.5%	21.2%	36.3%	25.205	(0.025)
42.66%	62.3%	5.8%	6.2%	55.0%	74.8%	23.450	0.092
42.55%	67.0%	5.3%	7.0%	27.8%	47.0%	23.555	0.080
68.5%	0.0%					16.949	
69.26%	45.9%	10.1%	57.3%	36.3%	0.0%	15.234	0.221
69.15%	19.1%	7.2%	3.8%	11.3%	26.5%	15.665	0.375
69.12%	28.7%	4.7%	4.4%	20.1%	47.3%	16.074	0.165
69.19%	38.3%	8.2%	4.4%	18.1%	35.7%	15.495	0.213
69.00%	46.1%	15.8%	4.3%	40.6%	39.6%	14.160	0.342
69.23%	38.2%	7.5%	2.5%	23.0%	31.5%	15.865	0.198
68.24%	28.8%	5.1%	1.9%	16.5%	24.3%	16.287	0.177
69.00%	19.1%	8.9%	2.0%	10.6%	2.2%	15.626	0.469
MDO							
42.5%	0.0%					21.903	
42.05%	21.9%	1.5%	5.1%	5.4%	6.9%	21.576	0.068
42.73%	33.2%	7.6%	2.5%	4.7%	2.9%	20.232	0.230
43.85%	44.4%	14.1%	1.1%	1.1%	-4.9%	18.822	0.317
43.30%	55.7%	16.0%	0.4%	2.1%	-7.2%	18.400	0.287
20.7%	0.0%					29.636	
21.81%	16.3%	2.5%	0.3%	-6.3%	4.9%	28.880	0.157
19.91%	33.1%	0.3%	1.6%	-24.0%	-7.5%	29.557	0.003
20.99%	42.5%	-3.5%	-7.9%	-16.3%	-3.5%	30.683	(0.081)
21.32%	54.7%	-2.5%	-8.3%	-5.7%	4.4%	30.368	(0.045)

Figure 8.6.2: M/V *Cabot* 2004 Emission Test Results

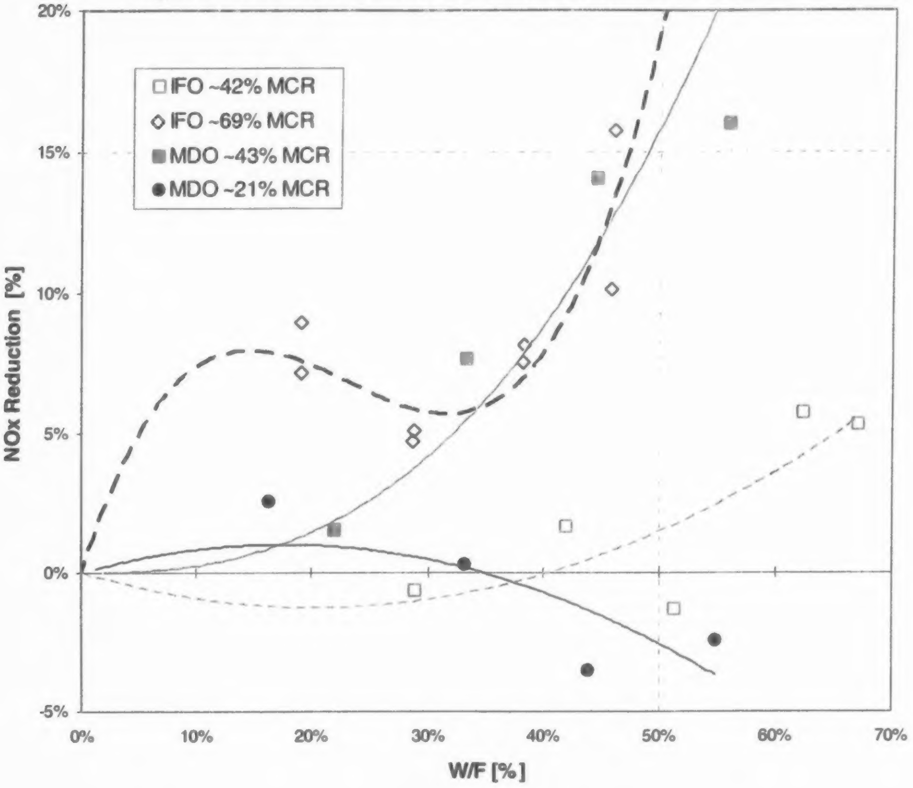


Table 8.6.1: M/V *Cabot* 2004 Emission Test Results

Actual Load % MCR	Actual % Water	Nox Reduction %	CO2 Increase %	CO Increase %	PM Increase %	NOx [g/kWh]	Effect.
42.7%	**0.0%**					**24.882**	
41.99%	28.8%	-0.7%	6.2%	6.4%	20.4%	25.046	(0.023)
41.72%	41.9%	1.7%	6.8%	16.1%	25.5%	24.469	0.040
42.53%	51.2%	-1.3%	5.5%	21.2%	36.3%	25.205	(0.025)
42.66%	62.3%	5.8%	6.2%	55.0%	74.8%	23.450	0.092
42.55%	67.0%	5.3%	7.0%	27.8%	47.0%	23.555	0.080
68.5%	**0.0%**					**16.949**	
69.26%	45.9%	10.1%	57.3%	36.3%	0.0%	15.234	0.221
69.15%	19.1%	7.2%	3.8%	11.3%	26.5%	15.665	0.375
69.12%	28.7%	4.7%	4.4%	20.1%	47.3%	16.074	0.165
69.19%	38.3%	8.2%	4.4%	18.1%	35.7%	15.495	0.213
69.00%	46.1%	15.8%	4.3%	40.6%	39.6%	14.160	0.342
69.23%	38.2%	7.5%	2.5%	23.0%	34.5%	15.865	0.198
68.24%	28.8%	5.1%	1.9%	16.5%	24.3%	16.287	0.177
69.00%	19.1%	8.9%	2.0%	10.6%	2.2%	15.626	0.469
MDO							
42.5%	**0.0%**					**21.903**	
42.05%	21.9%	1.5%	5.1%	5.4%	6.9%	21.576	0.068
42.73%	33.2%	7.6%	2.5%	4.7%	2.9%	20.232	0.230
43.85%	44.4%	14.1%	1.1%	1.1%	-4.9%	18.822	0.317
43.30%	55.7%	16.0%	0.4%	2.1%	-7.2%	18.400	0.287
20.7%	**0.0%**					**29.636**	
21.81%	16.3%	2.5%	0.3%	-6.3%	4.9%	28.880	0.157
19.91%	33.1%	0.3%	1.6%	-24.0%	-7.5%	29.557	0.008
20.99%	43.8%	-3.5%	-7.9%	-16.3%	-3.5%	30.683	(0.081)
21.32%	54.7%	-2.5%	-8.3%	-5.7%	4.4%	30.368	(0.045)

The TDC WIS system was specifically designed to inject water in the manifold in the liquid state, in the hope that the water injected would find its way into the cylinder remaining in the liquid state. Charge air humidification was deemed not possible; given the low operating scavenge temperature of the engine. The only way to get a sufficient amount of water into the cylinder was as a finely atomised liquid (droplets small enough to remain suspended in the air stream). The 2004 trials used a single point injection system. The trial data analysis revealed that the cylinders nearest to the injection point were getting most of the water injected, with massive coalescing occurring on the walls of these cylinders and in the scavenge trunk. The cylinders furthest from the injection point were receiving almost no water except for the saturated vapour resulting from evaporation at the scavenge temperature.

Pertinent notes and conclusions from this dataset are:

- Water injection system achieves NOx reductions of up to ~16%.
- In generally, NOx reduction increases with W/F ratio. The exception is at 21% MCR burning MDO; NOx appears to increase marginally ~ 2 to 3% with increasing W/F ratio. This could be combustion related attributed to relatively low load.
- At similar load (42% and 43% for IFO and MDO respectively, square markers on Figure 7.6.2), NOx reduction is much greater for the more the distillate fuel (MDO). At 50% W/F trends show ~15% reduction with MDO and ~3% reduction with IFO.
- Test report noted some cylinder knocking both with and without the WIS active.
- There is a fair amount of scatter in the summarized data.
- Results presented above are not cycle weighted.

8.7 M/V *Cabot* 2005

In March 2005, TDC conducted additional trials onboard the M/V *Cabot* [45, 46]. TDC had concluded that injection at the intake manifold in the first tests (Section 8.6) resulted in an uneven distribution of injected water amongst the engine cylinders (i.e. cylinders closest to the injection point getting too much water while cylinders furthest from the injection point were getting very little). To address this concern, a multiple injection point system was designed with continuous water injection with nozzles positioned in the air intake manifold at each cylinder location.

Emission testing was conducted in March 2005 with MDO and IFO at various rpm and water flow rates. Figure 8.7.1 summarizes the test results. Note in Table 8.7.1, the bold figures for NOx [g/kWh] are the averages of all baseline (no WIS) data for the corresponding bold %MCR value. These values are not used to derive line NOx reduction percentages. These are derived from averages of the baseline tests done immediately before and after the line WIS test (and not the average of all baseline data at the corresponding engine load (%MCR).

Pertinent notes and conclusions from this dataset are:

- Water injection system achieves NOx reductions of up to ~33.8%.
- NOx reduction increases with W/F ratio.
- NOx reduction at 66-69% MCR greater for MDO below 45% W/F and greater for IFO above ~45%. No such fuel quality crossover point evident for 47-48% load.
- NOx reduction increases with engine load and W/F ratio for both IFO and MDO. The magnitude of percentage reduction is greater for MDO.
- Results presented above are not cycle weighted.

Table 8.7.1: M/V *Cabot* 2005 Test Results Summary

Actual Load % MCR	Actual % Water W/F	NOx Reduction %	CO2 Increase %	CO Increase %	PM2.5 Increase %	PM10 Increase %	NOx [g/kWh]	Effect.
IFO								
36.9%	0						24.696	
36.9	45.3	4.2	6.3	28.3	39.2	28.9	23.650	0.094
48.4%	0						20.321	
49.1	35.1	2.3	5.3	10.1	26.8	40.8	19.300	0.065
48.2	71.0	7.8	7.4	27.1	66.8	62.0	19.347	0.110
48.1	71.1	5.5	10.1	20.2	34.0	20.0	19.123	0.077
69.1%							18.697	
69.1	36.2	18.7	4.0	11.9	13.1	11.8	15.256	0.518
69.8	35.1	18.0	4.8	8.6	5.3	-7.3	15.570	0.498
68.7	70.2	33.8	8.4	25.2	20.6	18.4	12.403	0.481
69.3	70.2	31.8	8.5	35.8	21.6	26.9	12.485	0.453
MDO								
21.18%							29.258	
21.0	36.5	4.5	4.0	19.1	10.1	13.9	27.798	0.123
21.2	70.3	6.5	5.1	31.2	13.1	9.1	27.510	0.092
46.70%							21.125	
47.2	35.1	4.5	6.7	16.7	43.8	38.8	18.999	0.127
47.6	35.1	11.0	3.1	11.0	44.7	46.4	19.609	0.312
44.8	71.6	13.0	6.5	19.7	31.5	32.4	19.665	0.181
47.1	71.1	10.2	8.8	24.2	20.9	21.2	17.947	0.144
66.72%							19.141	
66.4	36.2	19.8	4.7	21.0	19.5	21.6	15.525	0.542
66.3	70.2	28.5	7.2	28.6	36.6	45.2	13.567	0.406

DATA ABOVE AVERAGED BY COMMON W/F VALUE								
Actual	Actual	Nox	CO2	CO	PM2.5	PM10	NOx	Effect.
IFO								
36.9	45.3	4.2	6.3	28.3	39.2	28.9	23.65	0.094
49.1	35.1	2.3	5.3	10.1	26.8	40.8	19.30	0.065
48	71	6.6	8.8	23.7	50.4	41.0	19.23	0.093
69	36	18.4	4.3	10.3	9.2	2.2	15.41	0.508
69	70	32.8	8.4	30.5	21.1	22.7	12.44	0.467
MDO								
21	36.5	4.5	3.98	19.05	10.10	13.88	27.80	0.123
21	70.3	6.5	5.08	31.22	13.12	9.11	27.51	0.092
47	35.1	7.7	4.90	13.83	44.22	42.61	19.30	0.220
46	71.4	11.6	7.51	21.97	26.19	26.79	18.81	0.133
66	36	20	4.71	21.04	19.53	21.56	15.52	0.542
66	70	28	7.21	28.61	36.65	45.25	13.57	0.406

Figure 8.7.1: M/V *Cabot* 2005 Test Results

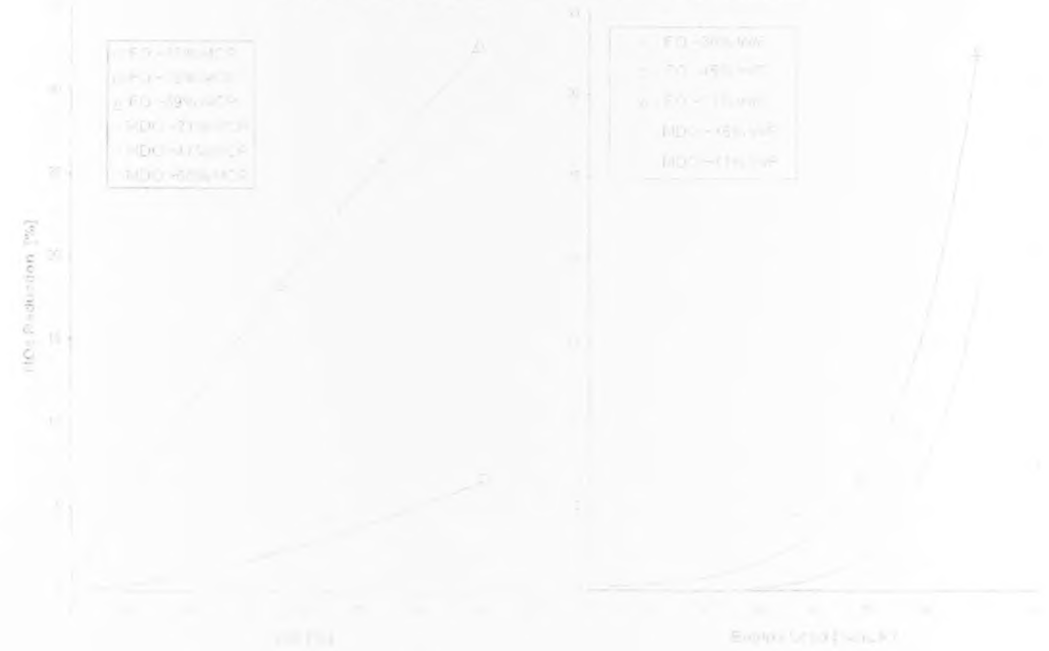
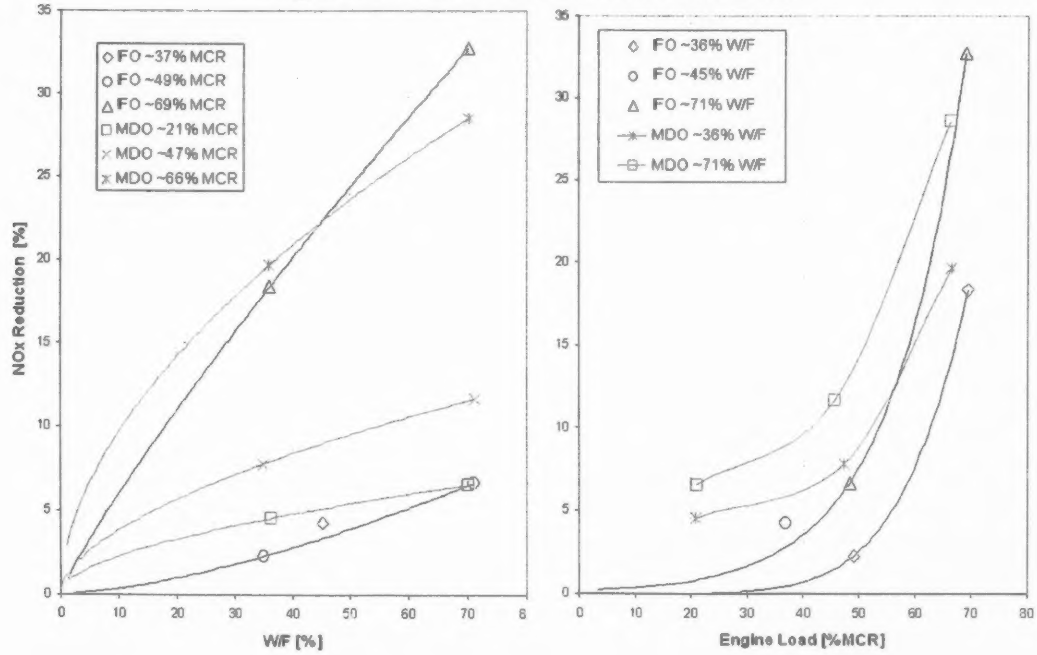


Table 8.7.1: M/V *Cabot* 2005 Test Results Summary

Actual Load % MCR	Actual % Water W/F	Nox Reduction %	CO2 Increase %	CO Increase %	PM2.5 Increase %	PM10 Increase %	NOx [g/kWh]	Effect.
36.9%	0						**24.698**	
36.9	45.3	4.2	6.3	28.3	39.2	28.9	23.650	0.094
48.4%	0						**20.321**	
49.1	35.1	2.3	5.3	10.1	26.8	40.8	19.300	0.065
48.2	71.0	7.8	7.4	27.1	66.8	62.0	19.347	0.110
48.4	71.1	5.5	10.1	20.2	34.0	20.0	19.123	0.077
69.1%							**18.697**	
69.1	36.2	18.7	4.0	11.9	13.1	11.8	15.258	0.518
69.8	36.1	18.0	4.6	8.6	5.3	-7.3	15.570	0.498
68.7	70.2	33.8	8.4	25.2	20.6	18.4	12.403	0.481
69.3	70.2	31.8	8.5	35.8	21.6	26.9	12.485	0.453
MDO								
21.18%							**29.258**	
21.0	36.5	4.5	4.0	19.1	10.1	13.9	27.798	0.123
21.2	70.3	6.5	5.1	31.2	13.1	9.1	27.510	0.092
46.70%							**21.125**	
47.2	35.1	4.5	6.7	16.7	43.8	38.8	18.999	0.127
47.6	35.1	11.0	3.1	11.0	44.7	46.4	19.609	0.312
44.8	71.6	13.0	6.5	19.7	31.5	32.4	19.665	0.181
47.1	71.1	10.2	8.6	24.2	20.9	21.2	17.947	0.144
66.72%							**19.141**	
66.4	36.2	19.6	4.7	21.0	19.5	21.6	15.525	0.542
66.3	70.2	28.5	7.2	28.6	36.6	45.2	13.567	0.406

DATA ABOVE AVERAGED BY COMMON W/F VALUE								
Actual	**Actual**	**Nox**	**CO2**	**CO**	**PM2.5**	**PM10**	**NOx**	**Effect.**
36.9	45.3	4.2	6.3	28.3	39.2	28.9	23.65	0.094
49.1	35.1	2.3	5.3	10.1	26.8	40.8	19.30	0.065
48	71	6.6	8.8	23.7	50.4	41.0	19.23	0.093
69	36	18.4	4.3	10.3	9.2	2.2	15.41	0.508
69	70	32.8	8.4	30.5	21.1	22.7	12.44	0.467
MDO								
21	36.5	4.5	3.98	19.05	10.10	13.86	27.80	0.123
21	70.3	6.5	5.08	31.22	13.12	9.14	27.51	0.092
47	35.1	7.7	4.90	13.83	44.22	42.61	19.30	0.220
46	71.4	11.6	7.51	21.97	26.19	26.79	18.81	0.163
66	36	20	4.71	21.04	19.53	21.56	15.52	0.542
66	70	28	7.21	28.61	36.65	45.25	13.57	0.406

Figure 8.7.1: M/V *Cabot* 2005 Test Results



- Since these were field trials the number of data points are limited. Ideally additional data points would be useful to populate graphs and aid in the definition of plots. Results presented above are not cycle weighted.
- NOx emissions reductions ranging from 2.3 to 33.8% come with significant increases in other emissions:
  - CO_2 increase of 3.1 to10.1%
  - CO increase of 8.6 to 35.8%
  - PM2.5 increase of 5.3 to 66.8%
  - PM10 increase of -7.3 to 62.0%
- The 2005 data set was more comprehensive than the Cabot 2004 test data. More frequent baseline (without water injection) measurements generally taken before and after each WIS active dataset.
- Injection of water occurred after the intercooler and no optimisation of intercooler operation with the exception of manually regulated the primary seawater coolant to maintain the outlet charge air temperature at 40°C was carried out due constraints imposed by the engine operation. This resulted in much lower intake temperatures than ideal and significantly reduced the humidification potential of the intake air.
- The low intake manifold temperature, and thus the maximum humidity that the intake air can hold, makes it difficult to achieve water W/F ratios any higher than 0.70 and thus limits NOx reductions.
- Significant liquid water carryover into the cylinder and could lead to significant cold corrosion problems.

8.8 WIS Data Comparisons

The test data analysed Section 8.1 thru 8.7 reflects engine emission test fitted with prototype retrofit water injection systems carried out in both laboratory and full-scale environments. The results reflect a range of fuel types, engines (ranging from heavy-duty diesel vehicle engines to high and medium marine engines) as well as WIS arrangements (Figure 8.1). The following sub-sections present what are thought to be some useful comparisons of these datasets.

8.8.1 IMO Comparison

Table 8.8.1.1 below summarizes the datasets discussed and presents the NOx emissions numbers for each with and without the WIS system utilized (see Sections 8.1 to 8.7 for details) along with the MARPOL Annex VI requirements. The following comments are made:

- The CAT3406E and Cummins NTC-350 are both heavy-duty truck engines of similar power and rpm but about 10 years difference in age (~20 year- and ~10 year-old engines respectively). Most marine engines of this power range are based on the manufacturers truck line (marine engine are 'marinized' truck engines).

  The NTC-350 as tested meets IMO emissions criteria (9.8 g/kWh) with the WIS active (NOx between 7.867 and 8.364 g/kWh) but does not meet IMO criteria without the WIS (11.651 g/kWh).

- The OSKI engines are of similar power and rpm to the engines noted above but older (presume original to 1979 ship construction) and overdue for a rebuild (with possible injection timing problems). Baseline uncontrolled specific NOx emissions of 38.219 to 43.851 far exceed IMO criteria. The WIS system tested was effective in reducing NOx emissions by ~25%, but this is still far in excess of IMO requirements.

- The WaveRider is a 1981 era high speed diesel engine with NOx emissions within IMO criteria. Tests demonstrate further NOx reduction (10-16.5%) possible with a WIS. Percentage reduction with WIS not as large as with older (higher initial NOx emission) engines.

Table 8.8.1.1: NOx Emission Tests Summary

CAT3406E

Engine Rating		Test	M.D.	+WIS BI	+WIS BI	+WIS BI	+WIS BI	+WIS AI	+WIS AI	+WIS AI	+WIS AI
RPM	KW	RPM	Base	0.302	0.423	0.444	0.454	0.388	0.401	0.469	0.505
1800	336	1800	1.401 / 1.314	1.086	1.019	0.979	0.939	0.858	0.893	0.859	0.861
Annex VI Requirement =			10.050								

Cummins NTC-350

Engine Rating		Test	M.D.	+WIS	+WIS	+WIS	+WIS
RPM	KW	RPM	Base	55psi	65psi	75psi	85psi
2100	261	2100	11.651	8.364	8.355	8.207	7.867
Annex VI Requirement =			9.800				

OSKI - NOx Emissions [g/kWh]

Engine Rating		Test	M.D.	+WIS	+WIS
RPM	KW	RPM	Base	LP	HP
1800	268	1201	43.851	33.257	35.269
		1563	40.365	30.978	30.039
		1660	38.219	29.502	28.430
Annex VI Requirement =			10.050		

WaveRider - NOx Emissions [g/kWh]

Engine Rating		Test	M.D.	M.D.	L.S.D.	L.S.D.
RPM	KW	RPM	Base	+WIS		+WIS
2300	805	1900	7.964	6.651	8.005	no data
		2000	8.715	7.616	8.651	7.392
		2100	9.582	8.609	9.008	7.966
Annex VI Requirement =			9.800			

QNW - NOx Emissions [g/kWh]

Engine Rating		Test	M.D.	+WIS	+WIS	+WIS	+WIS
RPM	KW	RPM	Base	1	2	3	4
750	3375	272	13.226	11.802	11.711	11.065	10.188
Annex VI Requirement =			11.973				

M/V Cabot #1

		IFO				MDO			
Engine Rating		LOAD	0 W/F	+WIS	+WIS	LOAD	0 W/F	+WIS	+WIS
RPM	KW	%MCR	Base	min	max	%MCR	Base	min	max
500	5370	42.7%	24.882	23.450	25.205	21%	29.636	28.880	30.683
		68.5%	16.949	14.160	16.287	42%	21.903	18.400	21.576
Annex VI Requirement =			12.984						

M/V Cabot #2

		IFO				MDO			
Engine Rating		LOAD	0 W/F	+WIS	+WIS	LOAD	0 W/F	+WIS	+WIS
RPM	KW	%MCR	Base	min	max	%MCR	Base	min	max
500	5370	37%	24.698	23.650	23.650	21%	29.258	27.510	27.800
		49%	20.321	19.123	19.300	47%	21.125	17.947	19.665
		69%	18.697	12.403	15.258	66%	19.141	13.567	15.525
Annex VI Requirement =			12.984						

- The QNW engines are second-generation medium speed marine diesel engines with lower baseline NOx emissions. The QNW without a WIS does not meet IMO criteria but is close to doing so. Retrofit of a simple water injection system would easily meet the IMO limit requirements.

- The MV Cabot engines are first generation marine engines with relatively high baseline NOx emissions. The WIS reduced NOx emissions by 10-34% for a range of W/F ratios and engine loads. With the WIS systems in operation at 70% load a NOx reduction up to ~34% was achieved which would make the engine IMO compliant.

8.8.2 Engines Tested in Laboratory

The CAT 3506E and Cummins NTC-350 lend themselves to comparison, as both are similar class (power and rpm) heavy-duty truck engines tested with the same WIS arrangement. Figure 8.8.2.1 below plots the percentage NOx reduction against W/F ratio. The before intercooler WIS test on each engine are complementary, each provides a different W/F range. The relationship between W/F ratio and NOx reduction percentage derived from combining the datasets is shown in Figure 8.8.2.1. Review of Tables 8.1.1 and 8.2.1 shows an increase in other emissions as NOx reduction increases.

Figure 8.8.2.1: Comparison of Engines Tested in Laboratory

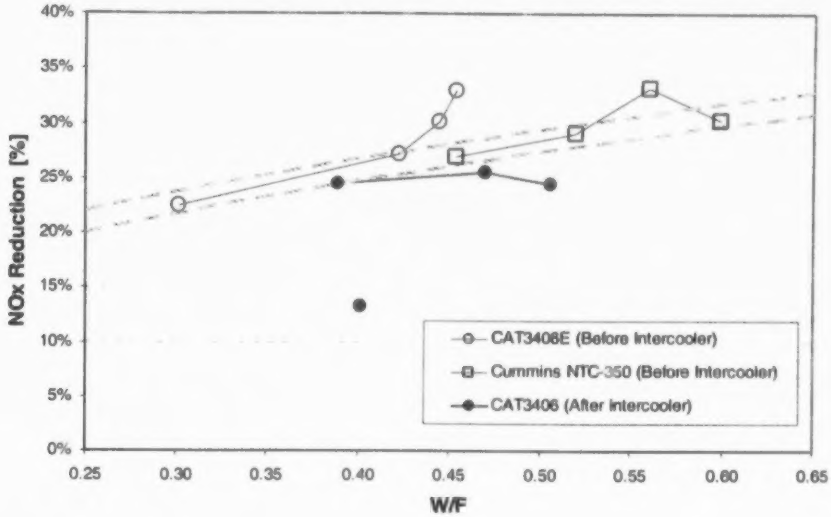


Figure 8.8.2.1 shows the WIS with water injection after the intercooler as being less effective as water injection before the intercooler. This may be representative of high-speed diesels burning MDO but not necessarily true of medium and low speed marine diesel engines burning IFO or HFO (see Section 2.1).

8.8.3 M/V *Cabot* Tests

The two WIS trials of the M/V *Cabot* provide opportunity for a comparison of the two different water injection system arrangements employed (single point and multipoint injection) and fuel quality (MDO and IFO).

Figure 8.8.3.1 plots baseline NOx emissions (without WIS) for both tests; average of all baseline tests completed for a given engine load. The dashed line shows a simple polynomial fit to all points plotted; this line implies that NOx emissions versus engine load (%MCR) are fuel quality independent. More data points would be required to establish what, is any characteristic difference exists between MDO and IFO curves. The curve plotted provides confidence in the repeatability of baseline tests. Larger scatter in IFO results may be explained by larger variance in fuel quality of IFO fuels compared to MDO or simply experimental/instrumentation error.

Figure 8.8.3.1: M/V *Cabot* Baseline NOx Emissions

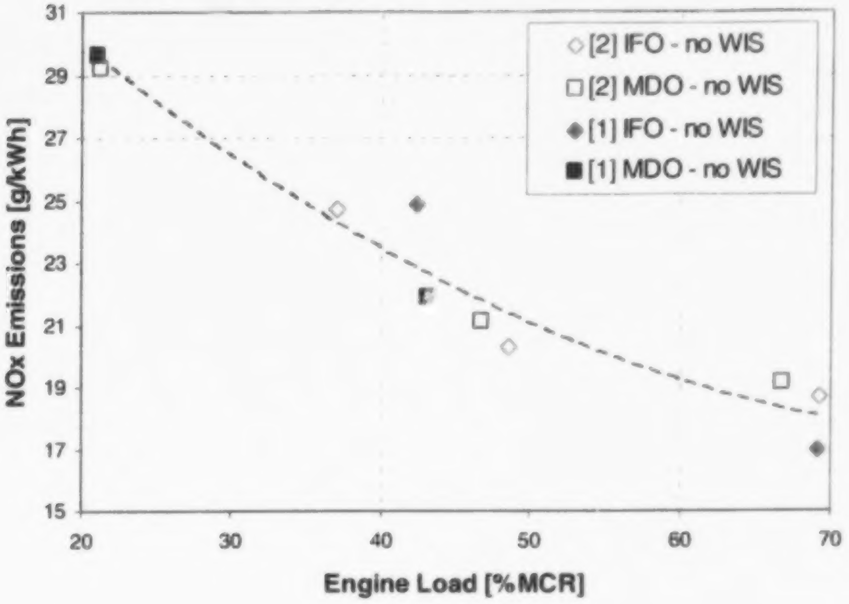


Figure 8.8.3.2 plots baseline NOx and CO emissions with the WIS active for the two tests at similar engine loadings. Conclusions are difficult due to limited number of points and scatter. However, the following may be inferred:

- The modified WIS configuration of the 2005 trials improves NOx reduction when burning IFO. This is marginal difference at ~43-48% load but significant at ~69% load.
- The modified WIS configuration of the Cabot 2005 trials appears to improve NOx reduction when burning MDO with a W/F ratio in the 50-70% range.
- Both tests show an increase in CO emissions with the WIS when burning either MDO or IFO. The 2005 WIS arrangement provides an improvement in CO emissions over the 2004 arrangement when burning IFO. The reverse is apparent when burning MDO.

Figure 8.8.3.3 plots the NOx 'Effectiveness' (a normalized comparison of NOx emission data). This plot highlights the significant improvement of the 2005 WIS configuration compared to the 2004 WIS configuration when burning IFO at ~69% MCR (open diamond markers at higher efficiency than solid diamond markers).

Figure 8.8.3.2: M/V *Cabot* 2004 & 2005 NOx and CO Reduction Comparison

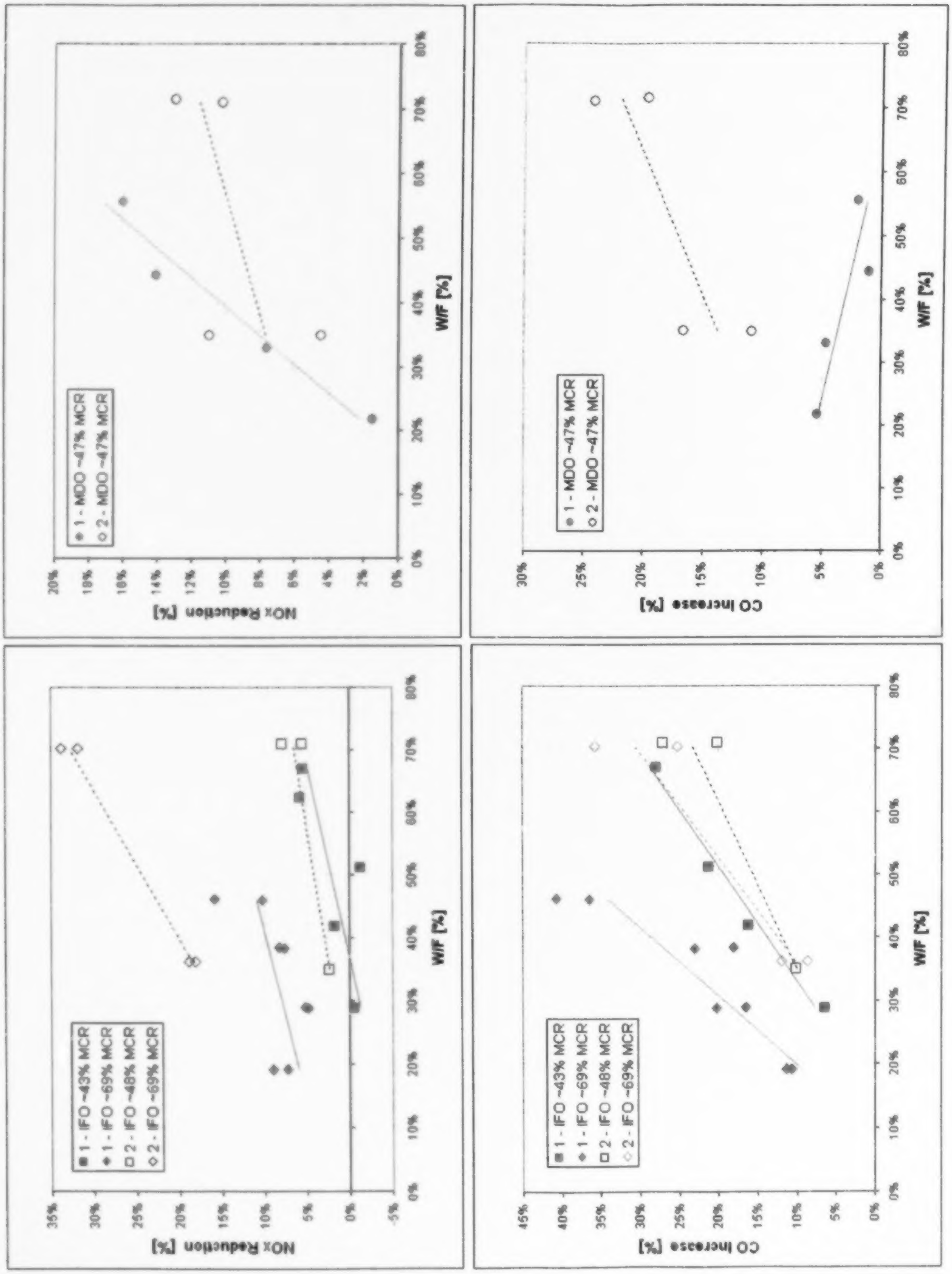
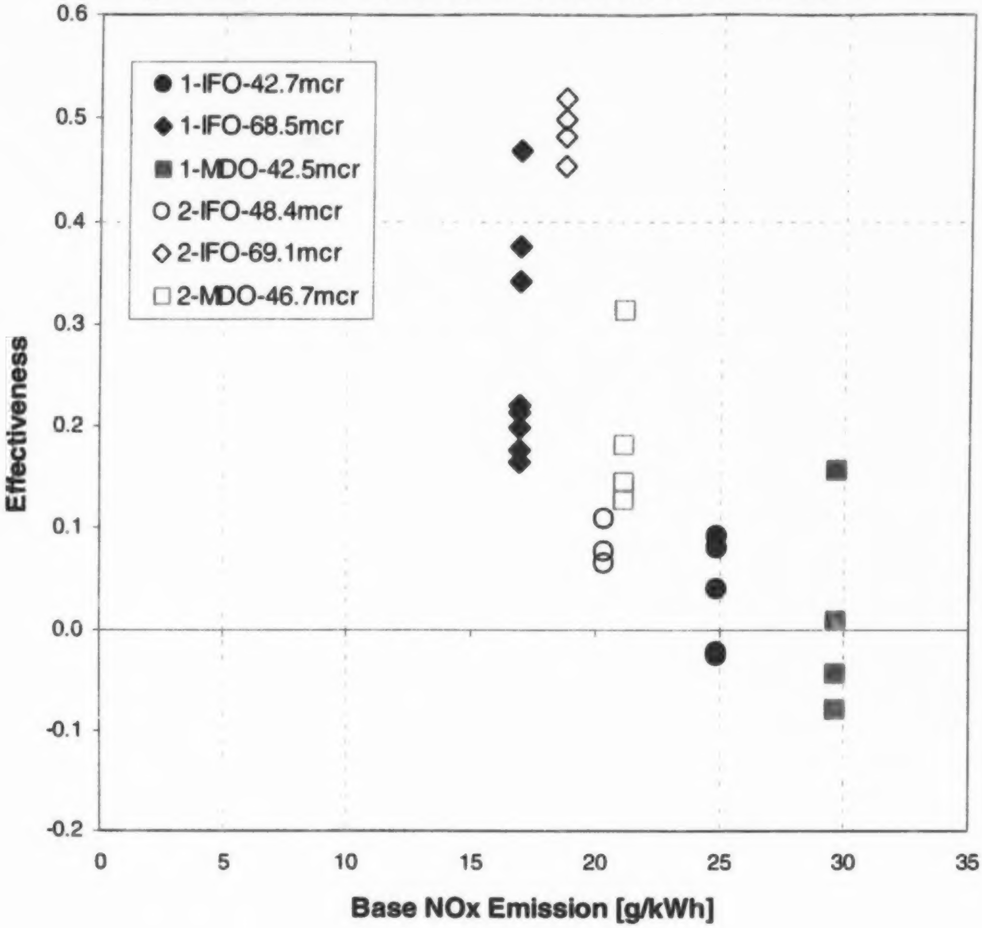


Figure 8.8.3.3: M/V *Cabot* 2004 and 2005 NOx Effectiveness



9. CONCLUSIONS

The following conclusions are based on the work completed and information presented in this report.

NOx and PM FORMATION

- The primary mechanisms for NOx formation during combustion are (i) Thermal NO, (ii) Prompt NO, (iii) N_2O Pathway, and (iv) Fuel Nitrogen Pathway. Process parameters that influence NOx formation (i.e., quantity of reactants, pressure, temperature, etc.) may effect a change in the quantity of NOx formed.

- Much of the current understanding regarding diesel combustion, NOx formation and reduction mechanisms is based on heavy-duty, high-speed diesel engines using distillate fuels. Less attention has been given to medium- and low-speed marine diesel engines burning heavy fuels. The nature of combustion in medium- and low-speed diesel engines operating on heavier fuels can differ from high-speed engines operating with on-road diesel fuel. However, it is expected that the mechanisms of charge dilution with water used to lower NOx emissions will be similar. The reduction in the flame temperature due to the reduced mole fraction of oxygen and subsequent increase in the mole fraction of relatively inert heat absorbing gases is expected to be most important. This will be most apparent on NOx formed by the thermal mechanism.

- NOx formation is primarily a function of combustion temperature. The two primary mechanisms in the combustion process are thermal NO and prompt NO, both of which are affected strongly by temperature, pressure, flame conditions, residence time and concentrations of key reacting species. Water introduced into the combustion process lowers the peak combustion temperature, which inhibits the formation of nitrogen oxides. Normally, high combustion temperatures promote PM oxidation and, inversely, lower combustion temperatures inhibit oxidation. Water injection reduces combustion temperatures, which inhibits oxidation and leads to the formation of sulphates and ash that make up PM emissions. The PM increase is linked to high sulphur content (about 1.5%) and high asphaltenes in high-suphur fuel. HFO oil contains a higher percentage of sulphur and metal oxides than MDO.

WATER-BASED NOx REDUCTION

- Water-based NOx reduction methods introduce water vapour into the combustion process, which affects the various NOx formation mechanisms. The primary effects are a reduction in combustion temperature (via heat of vaporization of water) and stochiometric change brought about by mass dilution of the combustion constituents (e.g., oxygen and nitrogen starvation).

- Of the water-based technologies investigated, intake air water injection / humidification appears to provide the greatest potential for NOx reduction. Sophisticated system implementations (CASS, HAM) using W/F ratios in the range of 2.5 to 4.5 are able to obtain NOx reductions in range of 60 to 80%.

- An excess of water injected into the cylinder either too early or too late in the combustion process can cause cooling of the cylinder, which may lead to increased ignition delay, engine knocking and retarded (or incomplete) combustion, especially for transient operation and at low loads.

INTAKE AIR WATER INJECTION / HUMIDIFICATION

- Maximum NOx reduction potential is a function of the maximum humidity that the intake air can hold while avoiding induction of liquid water into the engine. For humidification after the intake compressor, the maximum humidity is determined by the minimum air temperature between the point of water injection and the combustion chamber. The saturation humidity of air increases exponentially with temperature so that in order to maximize the NOx reduction potential, the minimum temperature in the intake manifold should be as high as the engine can tolerate without operating difficulties.

- The best conditions for water injection into the intake air stream are usually encountered immediately after the turbocharger. Temperatures here are highest and thus droplet evaporation time is shorter. Droplet evaporation time decreases exponentially with temperature and increases linearly with pressure.

- The maximum tolerable droplet size to ensure good evaporation (and thus intake air humidification) depends on the temperature of the air and the location of the water injection nozzles. The injection of large water droplets is permissible at higher air temperatures and when the location of injection is upstream of the combustion chamber, thus providing longer transit/residence time of water droplet and longer time for evaporation to take place.

- Water evaporation can result in a significant temperature drop in the humidified intake air. This effect may be compensated for by pre-heating the water using waste engine heat from exhaust or cooling systems. Control of the flow through the intercooler operation needs to be adjusted (coolant flow control) in order to ensure that condensation does not occur after the intercooler and so that intake air humidity and thus NOx reduction potential is maximized.

DIRECT IN-CYLINDER INJECTION

- Stratified injection (fuel-water-fuel through the same injector) allows more precise water placement into the combustion zone than with separate water and fuel injectors. The major drawback of stratified direct water injection is that the system configuration is complex and expensive, involving a complicated nozzle and considerable adjustment to the existing system. Experimental and theoretical evidence indicates that stratified injection has the highest potential (of the direct in-cylinder injection methods) for NOx reduction without increasing other harmful emissions or compromising fuel efficiency and engine operability.

- Direct water injection (DWI) using a separate nozzle for fuel and water is a more economical solution and provides better overall engine operability than stratified injection. DWI is a good design option for new engines in that it has minimal effect on cold start and lubricating oil water contamination. Test data show that simple DWI systems can reduce NOx emissions on the order of 30%.

FUEL-WATER EMULSIFICATION

- Fuel-water emulsion injection into the cylinder is another method for NOx emissions reduction. Due to its simplicity in system installation and operation, it has found favour in several engine retrofit applications. However, the W/F ratio that can be utilized is limited by fuel nozzle capacity, since the emulsion displaces the fuel required to maintain power output.

- Emulsions (especially micro-emulsions) are very effective in directing the water towards the flame/combustion zone, due to improved atomization and mixing that occurs prior to combustion. At lower W/F ratios (W/F < ~30%), smoke is often reduced and fuel consumption not adversely affected.

WIS TEST DATA

- A number of datasets, from simple water injection systems (water spray into charge air supply/manifold) to sophisticated engine humidification systems, are summarized in this report. This provides an insight into attainable NOx emissions reduction with relatively simple water injection systems.

- Shipboard emissions data collection is a complex process. Besides the logistics and expense of data collection, there are some inherent problems that can result in data scatter: operation in seaway means loading is variable (currents, waves, wind); environmental conditions, and thus certain engine operation parameters, may vary depending on time test conducted (i.e., cooling water temperature, intake air humidity etc.); results vary depending on engine condition/maintenance; and fuel characteristics may be hard to define (i.e., fuel mixed in tanks, contamination when switching from fuel types). The data obtained from each trial is useful in that it is representative of real-life conditions and allows general conclusions to be made. However, it is difficult to draw precise conclusions from the datasets collectively.

- The TDC dataset reviewed was the most robust and detailed of the prototype WIS arrangements. Of particular interest was that it allowed a comparison between two designs of water injection on the same engine (2004 trials with water injection at intake manifold and 2005 trials with injection opposite each cylinder). During the 2005 trial, NOx reduction was increased from ~10% to ~20% at ~69% engine load with a W/F ratio of ~0.35. A general conclusion that can be made from the MV *Cabot* datasets collectively is that NOx reductions up to ~34% can be readily achieved with a simple water injection system and W/F ratios of less than 0.70.

ENGINE MAINTENANCE AND OPERATION

- While it may not be necessary or even possible to completely prevent the condensation of some sulphuric acid on the cylinder liner, great care must be taken to ensure that any water-based NOx control strategies do not contribute to the problem. The most important consideration is that liquid water must not be allowed to contact the cylinder liner. The major engine manufacturers take great care to avoid liquid water in the cylinder as this can cause a number of problems. While small amounts of strong acid solutions can actually be acceptable, introducing liquid water on the liner can dilute these strong acid solutions. The resulting dilute acid solutions can lead to sudden and severe wear. Introducing liquid water will not only dilute the acid but also increase the amount of aqueous phase on the liner and lead to a breakdown of the hydrodynamic lubrication layer and very high wear rates.

- While new engines with advanced cylinder liner and piston technology can operate with intake air near saturation, this may not be the case for older engines. Caution should be exercised when considering intake humidification for older engines to avoid cylinder liner corrosion. Humidifying the intake air increases the dew point of sulphuric acid and can lead to more acid condensing on the cylinder liner. Intake humidity levels need to take into account the temperatures of the cylinder liner at all conditions under which it is applied in order to avoid cold corrosion issues. One of the critical aspects of humidifying the intake air is to ensure complete evaporation of the water before the humidified air enters the combustion chamber. Liquid water carryover into the cylinder can cause (i) significant cold corrosion problems through its interaction with sulphuric acid that forms from fuel sulphur and (ii) lubricity problems due to contamination of lube oil.

REGULATORY

- MARPOL Annex VI entered force on 19 May 2005. This regulatory vehicle defines limits for sulphur oxide (SOx) and nitrogen oxide (NOx) emissions from ship exhausts. Canada currently proposes to ratify MARPOL Annex VI by 2006/07.
- The MARPOL Annex VI defined emission limits for NOx are not particularly demanding and will likely become more stringent in the future, falling in line with EPA and EU regulations.

10. RECOMMENDATIONS

The following bullets present recommendations based on the work completed and information presented in this report.

- Additional data points are always useful in trying to characterize WIS performance. Further testing on the M/V *Cabot* could help better define some of the curves plotted: for example, extension of the W/F range, additional data points within the W/F range to determine curve shape, and repetition of data points so that scatter may be reduced through elimination of anomalous data points.

- The available WIS datasets presented are for simple systems with limited engineering refinement. These tests were designed to simply humidify intake air to demonstrate and measure a NOx reduction. Optimization of a WIS would require extensive testing to fine-tune parameters such as droplet size or density, temperature and pressures of fuel/air mixture, etc. System fine-tuning is best done on testbed engines where engine loading, operation and maintenance, and fuel quality can be more precisely controlled; removal of real ship engine 'noise' should minimize data scatter.

- The need for additional testing is dependent on what is hoped to be accomplished. If the aim is to produce a database of engine types with data regarding NOx emissions with and without a simple WIS, then additional engine testing similar to that summarized in this report should be completed. A larger database of test data would allow quick assessments of an engine such as: (i) engine is too old, no chance of it meeting IMO criteria, (ii) engine should meet IMO criteria with a simple WIS, or (iii) relatively modern engine that should meet IMO criteria without a WIS. Alternatively, if the aim is to fine tune and optimize a simple WIS, then testing should be completed on the testbed where test parameters can be more tightly controlled.

- An assessment of the Canadian fleet should be made to identify the most common engine types, power ranges and age. This would help define which engine types to consider for addition to the test database mentioned above and would assist regulators in determining the impact of new regulations, which in turn may help define any 'sunset' clauses or grandfathering required of new regulations.

- Following on from the above, manufacturers of engines common to the Canadian fleet should be contacted to establish which, if any, manufacturer-produced or endorsed add-ons or modifications are available.

- Cost estimating should be completed for simple WIS systems such as those for which test data was presented in this report. This should include not only the add-on WIS system cost but also operational costs. Cost-benefit analyses can then be made of WIS retrofits versus re-powering with a modern emission-compliant engines or alternate emission reduction upgrades from the engine manufacturer (i.e., modern fuel injection system – electronic vs. mechanical).

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